

Title: Morphological Analyses Using  
3D Building Databases:  
Los Angeles, California

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# **Morphological Analyses using 3D Building Databases: Los Angeles, California**

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## Abstract

*This report summarizes our calculations of building morphological characteristics for a 12.0 km<sup>2</sup> area centered around the downtown of Los Angeles, California. A three-dimensional building dataset (i.e., urban terrain), digital orthophotos, detailed land use/cover information, bald-earth topography, and roads were integrated and analyzed using a geographic information system (GIS). Building height characteristics (e.g., mean height, variance of height, height histograms) were determined for the entire study area and broken down by land use type. Other parameters describing the urban morphology that were calculated include the building plan area fraction ( $\lambda_p$ ), building area density ( $a_p(z)$ ), rooftop area density ( $a_r(z)$ ), frontal area index ( $\lambda_f$ ), frontal area density ( $a_f(z)$ ), complete aspect ratio ( $\lambda_c$ ), building surface area to plan area ratio ( $\lambda_B$ ), and the height-to-width ratio ( $\lambda_s$ ). Aerodynamic roughness length ( $z_o$ ) and zero-plane displacement height ( $z_d$ ) were calculated for the entire study area and for each land use type using standard morphometric equations and the computed urban morphological parameters.*

*The urban morphological parameters were calculated for the entire study area, as a function of land use type, on spatial grids, and in some cases as a function of height above ground elevation. Building statistics were correlated to underlying land use using two different land use classification schemes: the seven USGS Anderson Level 2 urban land use types and a second scheme containing more detailed residential and commercial categories. Most of the morphometric parameters that we calculated were found to be similar to values computed for other cities by other researchers. The results indicate that the calculated urban morphological parameters are significantly different between different land use types. Significant differences were also noted between subcategories of residential land use. Moreover, commercial areas were found to have very different morphological characteristics as compared to other urban land use types, primarily because commercial areas have pockets of densely packed tall buildings. The findings presented herein are intended to be utilized in urban canopy parameterizations found in mesoscale meteorological and urban dispersions models.*

## 1.0 Introduction

Describing the urban terrain and land use/land cover (LULC) characteristics accurately is vital for urban planning, environmental management, environmental modeling, and many other applications. Comprehensive urban databases with urban terrain and LULC information are essential inputs for numerous meteorological modeling applications, e.g., simulating the atmospheric flow over cities, quantifying energy fluxes radiated to and from urban surfaces, determining the fate and transport of atmospheric contaminants in built-up areas. Urban terrain elements can be broadly classified as natural landscape, ornamental vegetation, buildings, impervious surfaces, or other infrastructure. Specific datasets required to describe the urban terrain in three dimensions include bare-earth digital elevation model (DEM), tree canopy and vegetative cover, land use/land cover, infrastructure, and building footprint outlines with height attribute.

The motivation for this research is the need to compute urban canopy parameters for mesoscale meteorological modeling and air quality applications (see Ratti et al. 2001 and Brown 1999). The research objectives are to collect detailed urban datasets in a geographic information system (GIS) environment, develop automated procedures to calculate urban canopy parameters, and integrate the urban canopy parameter values with detailed LULC datasets to derive relationships between the parameters and urban land use type. This report describes these efforts for a 12-km<sup>2</sup> section centered on the downtown of Los Angeles, California. Section 2.0 of this report describes the accumulated datasets in the Los Angeles GIS database, Section 3.0 details the calculation procedures for the morphological parameters and presents the results from the calculations, and Section 4.0 summarizes the report.

## 2.0 Los Angeles Urban Database

### 2.1 Urban Morphology

Urban building, tree canopy, and DEM datasets can be purchased from commercial vendors or derived in-house. The resolution, accuracy, cost, and level of detail are important dataset characteristics to consider during the acquisition phase. The basic level of information supplied with purchased building datasets is typically the building footprint and the elevation of the rooftop. More sophisticated (and likely more expensive) datasets will have greater detail of the building (e.g., representation of rooftop structures) and include additional pieces of information (e.g., rooftop color and pitch, materials). Table 1 lists several commercial vendors that provide building, tree canopy, and DEM datasets and other digital urban data products. Digital building datasets can currently be obtained for numerous U.S. and international cities and more are rapidly becoming available.

**Table 1.** Commercial vendors of building datasets

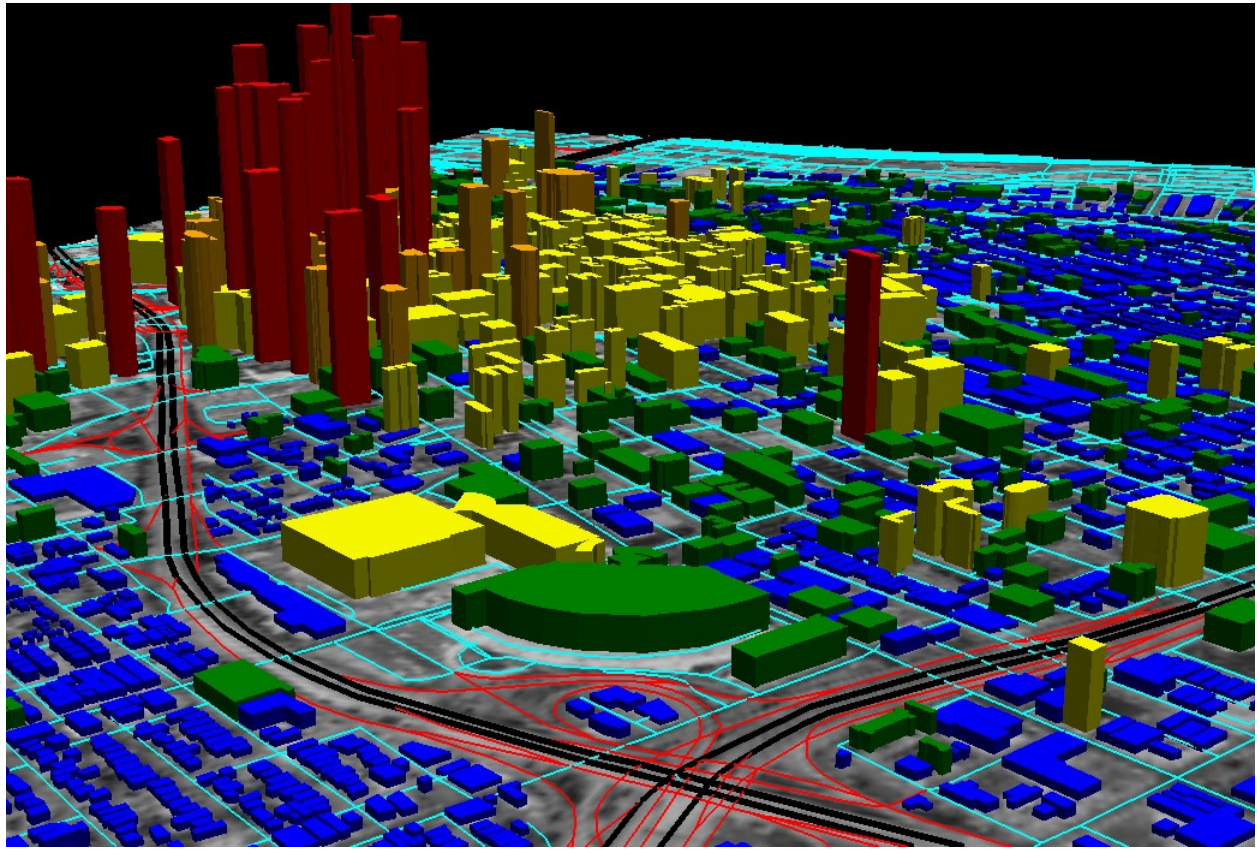
Vendor	Web Site
i-cubed	<a href="http://www.i3.com">www.i3.com</a>
Istar USA	<a href="http://www.istar.com">www.istar.com</a>
The Gemi Store	<a href="http://www.gemistore.com">www.gemistore.com</a>
Urban Data Solutions, Inc.	<a href="http://www.u-data.com">www.u-data.com</a>
Vexcel Corporation	<a href="http://www.vexcel.com">www.vexcel.com</a>
Terrapoint (lidar)	<a href="http://www.transamerica.com/business_services/real_estate/terrapoint/default.asp">www.transamerica.com/business_services/real_estate/terrapoint/default.asp</a>

For the Los Angeles downtown area we obtained a section of the Aerotopia 3D cities dataset. Aerotopia distributes their data through a number of commercial vendors, including some of those listed above in Table 1. The Aerotopia dataset contains building footprints with rooftop elevation as an attribute. In most cases the vendor can provide the dataset in a variety of generic vector or raster data formats or data formats specific to commercial software packages (e.g., ESRI shape files). Building representations in the Aerotopia dataset do not contain detailed representations of rooftop structures, roof pitch, and other characteristics. The buildings footprints are represented as 2D polygons in shape file format. Tree canopy data were not obtained for the study area because analysis of an aerial photograph indicated that few trees or bushes are present in downtown Los Angeles, even in the high-density single-family residential areas. The Los Angeles dataset we obtained covers an area of 17.1 km<sup>2</sup>, encompassing the downtown region and adjacent areas of predominantly residential, industrial, and commercial land uses.

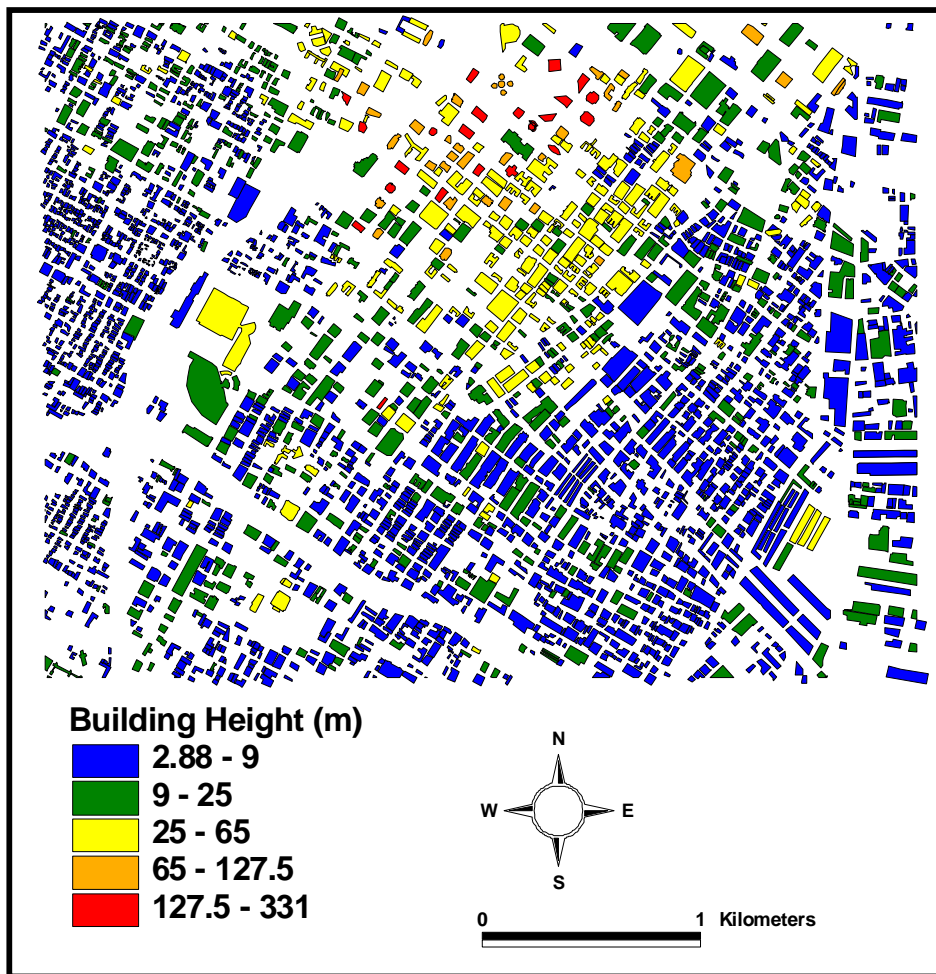
One limitation of the basic Aerotopia product is the absence of residential buildings with rooftop heights below approximately 10 m. To overcome this limitation we digitized missing buildings using high-resolution (1-meter pixel size) aerial photographs. We then assigned rooftop elevations based on adjacent buildings that appeared to be of equal height or, where possible, by counting the number of stories. Building heights were then assigned assuming that one-story buildings were 4 m and each story in multiple-story buildings was 3.5 m. These height-per-story values were determined from an analysis of over 100 buildings in the Los Angeles area for which we had both building height and story information. The analyses described in this report are based on a 12-km<sup>2</sup> rectangular area extracted from the 17.1 km<sup>2</sup> total dataset area. We focused the study on the 12-km<sup>2</sup> area because we wanted to eliminate the fringe areas of the building dataset, which had a significant number of missing buildings. For the 12-km<sup>2</sup> study area the original Aerotopia dataset contained 2,062 buildings. The modified dataset (after additional buildings were digitized) contained 3,353 structures (see Figures 1 and 2).

## ***2.2 Urban Land Use/Land Cover (LULC)***

LULC data for areas in the United States can be obtained from several sources including federal agencies (e.g., U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA)), state agencies, local/regional planning agencies, universities, researchers, commercial vendors, and others. In general, datasets obtained from the federal, state, local/regional planning agencies, universities, or other researchers are free or cost a nominal fee. Commercial vendors on the other hand will provide a specific product with additional quality control for a more substantial price. For this study we chose to use existing datasets that can be obtained free-of-charge. An analysis of the available LULC datasets for the Los Angeles area indicated that the Southern California Association of Governments (SCAG) dataset was more accurate and had the highest level of spatial resolution and classification detail compared to the USGS LULC dataset and the National Land Cover Dataset (NLCD) (Burian and Brown 2001). The SCAG dataset was therefore selected for use in the analyses described in this report. The SCAG dataset has a spatial resolution of approximately 0.25 ha (2500 m<sup>2</sup>) and is based on low-altitude aerial photographs collected during 1993. The SCAG dataset is classified according to a modified Anderson Level III/IV classification system, with 125 LULC classes, more than 100 of which are urban (see Appendix 1).



**Figure 1.** 3-D view from the southwest of the modified Los Angeles building database. The domain covers a 3-km by 4-km area. Buildings are color coded by height (see Figure 2) and are overlaid onto a street map and digital orthophoto.



**Figure 2.** Plan view of the modified Los Angeles building database. The domain covers 12 km<sup>2</sup>. Buildings are color-coded by height; many of those below 10 m were manually digitized using aerial photos.

A major objective of this research project is to derive relationships between urban canopy parameters and urban land use type. To meet this objective we need to spatially relate urban canopy parameters with a manageable number of urban land use types. The urban land use types and method of aggregation to use in such an analysis is subject to debate. We decided to use two urban land use classification schemes: the first corresponding to the USGS Anderson Level 2 categories and the second with more detailed classification of the Residential, Commercial & Services, and Other Urban or Built-up land use categories. Table 2 summarizes the land use types in each classification scheme. The seven categories for the first scheme are (1) Residential, (2) Commercial & Services, (3) Industrial, (4) Transportation/Communications/Utilities, (5) Mixed Industrial & Commercial, (6) Mixed Urban or Built-up, and (7) Other Urban or Built-up. This is the same scheme used to classify urban land use in the USGS dataset. The second classification scheme contains sub-categories for Residential, Commercial & Services, and Other Urban or Built-up land use types. The Residential category is divided into four sub-

categories: (1) Low-density Single-family, (2) High-density Single-family, (3) Multifamily, and (4) Mixed. Building density and vegetation characteristics are expected to be significantly different between the four types of residential land use. The Commercial & Services category is divided into two sub-categories: Non-high-rise and High-rise. The Other Urban or Built-up category is also divided into two sub-categories: Predominantly Vegetated and Predominantly Built-up. Appendix 2 contains detailed descriptions of each of the land use types used in the building analysis.

The mapping from the 100+ SCAG urban land use types to our two aggregated land use schemes (hereafter called the 7-category scheme and the 12-category scheme) are shown in Appendix 3. In order to analyze and define the characteristics of high-rise areas throughout the city, not just those in the Commercial & Services land use, a new land use category called Urban High-rise was defined by using the SCAG high-rise categories, e.g., apartments, condominiums, office buildings. In addition, a Downtown Core Area land use category was defined in order to investigate the characteristics of the city center. The Downtown Core Area was delineated by based on a digital orthophoto. These two newly-defined classes will overlap with the land uses in our two classification schemes, but are needed so we can analyze and define the characteristics of high rise and city center areas of cities.

The 12-km<sup>2</sup> study area is a highly urbanized region of Los Angeles consisting of a part of the downtown region (containing high-rise buildings), as well as High-density Single-family Residential and Industrial areas. The land use distribution listed in Table 2 suggests that most of the land use is Commercial & Services and Industrial with a small fraction of Residential and Transportation/Communications/Utilities. This is typical of a major city downtown area. Figure 3 shows the SCAG dataset for the 12-km<sup>2</sup> study area in Los Angeles after aggregation to our 12-category land use scheme. Notice that the intersection of the two major highways (shown in black) occupies a significant amount of space in the study area.

Note also that Low-density Single-family Residential is not present in the study area. Low-density is defined as Residential land use containing less than 8 detached single-family housing units per hectare, while high-density is defined as Residential land use with higher housing unit density. The 8 housing units per hectare corresponds to a standard 1/3-acre lot used in many urban developments in the U.S. Therefore, the high-density category will include subdivisions with 1/3-acre lots or smaller, while the low-density will be 1/2-acre or larger. Although the study area in Los Angeles does not contain Low-density Single-family Residential land use, the classifications used in this study will be used for analyses of other cities and other parts of Los Angeles where low-density residential is present.

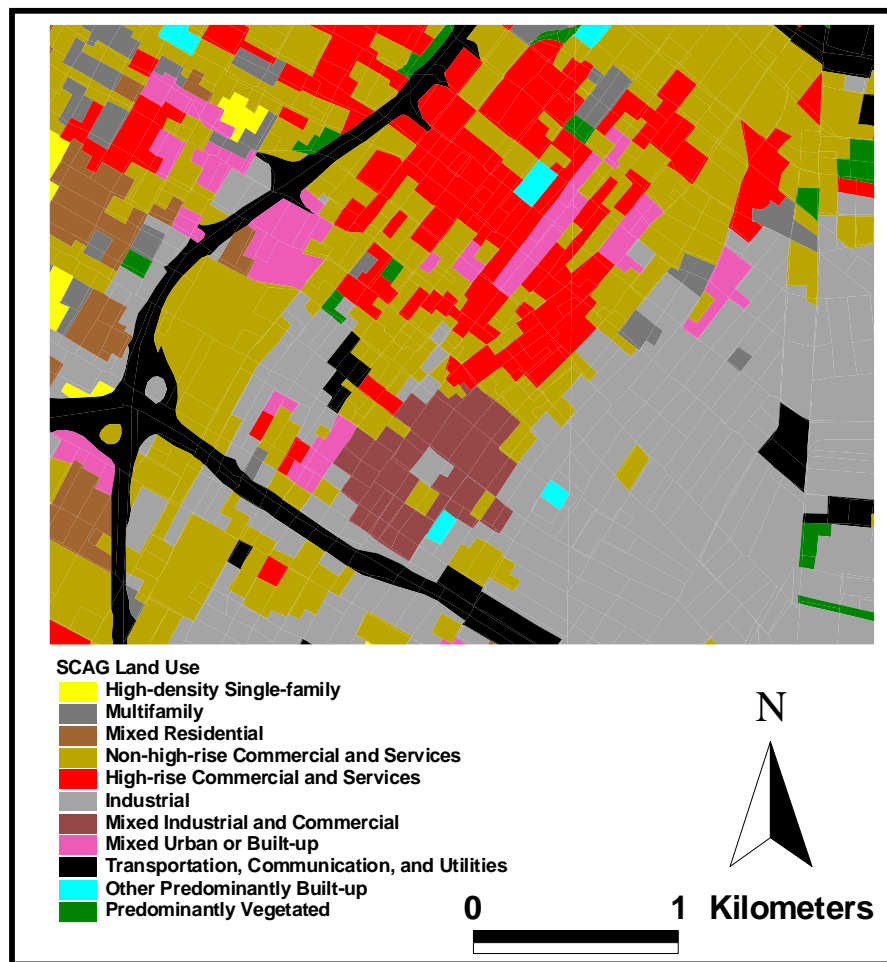
Following aggregation, the SCAG LULC dataset was intersected with the building dataset using GIS to identify which buildings were associated with which land use type. Fortran codes and Avenue scripts were written, and along with standard ArcView GIS functions, they were used to calculate a suite of urban morphological parameters. The calculation procedures and the results of the analyses are described next in Section 3. In particular, we have computed building height histograms, the mean building height, the standard deviation of the building height, the building plan area fraction ( $\lambda_p$ ), building area density ( $a_p(z)$ ), rooftop area density ( $a_r(z)$ ), frontal area index ( $\lambda_f$ ), frontal area density ( $a_f(z)$ ), complete aspect ratio ( $\lambda_c$ ), building surface area to plan

area ratio ( $\lambda_B$ ), height-to-width ratio ( $\lambda_S$ ), the roughness length ( $z_o$ ), and the displacement height ( $z_d$ ).

**Table 2.** Urban land use coverage in our 12-km<sup>2</sup> study area

Land Use Class	Area (ha)*	Percent of Total (%)
<b>Residential</b>	<b>86</b>	<b>7</b>
Low-density Single-family (< 8 units/hectare)	0	0
High-density Single-family ( $\geq 8$ units/hectare)	8	1
Multifamily	39	3
Mixed	39	3
<b>Commercial &amp; Services</b>	<b>519</b>	<b>43</b>
Non-high-rise	358	30
High-rise	161	13
<b>Industrial</b>	<b>372</b>	<b>31</b>
<b>Transportation/Communications/Utilities</b>	<b>98</b>	<b>8</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>43</b>	<b>4</b>
<b>Mixed Urban or Built-up</b>	<b>58</b>	<b>5</b>
<b>Other Urban or Built-up</b>	<b>24</b>	<b>2</b>
Predominantly Vegetated	16	1
Predominantly Built-up	8	1
<b>Urban High-rise</b>	<b>186</b>	<b>16</b>
<b>Downtown Core Area</b>	<b>250</b>	<b>21</b>

\* The areas are given in hectares (ha) (100 ha = 1 km<sup>2</sup>).



**Figure 3.** SCAG LULC dataset for the 12-km<sup>2</sup> study area aggregated to building analysis land use classification.

### 3.0 Derivation of Urban Morphological Parameters

#### 3.1 Building Height Characteristics

Average building height yields information on the depth through which the urban canopy directly impacts the atmosphere. Average building height (multiplied by a proportionality constant) can be used as a first-order approximation of the surface roughness  $z_0$  (see Section 3.10). Surface roughness is used in air quality and meteorological models to account for enhanced mixing and the drag effects of the underlying surface. Canopy height is often used as the length scale in the canopy layer. Urban field experiment data evaluations have suggested that similarity theory is valid somewhere above the canopy height. Below canopy height, drag parameterizations can be used to account for reduced air flow due to the urban fabric. Variation in canopy height may prove to be important in parameterizations of turbulence production.

In this section we summarize the height characteristics of buildings in the 12-km<sup>2</sup> study area. The mean and standard deviation of building height were calculated using the following equations:

$$\bar{h} = \frac{\sum_{i=1}^N h_i}{N} \quad (1)$$

$$s_h = \sqrt{\frac{\sum_{i=1}^N (h_i - \bar{h})^2}{N - 1}} \quad (2)$$

where  $\bar{h}$  is the mean building height,  $s_h$  is the standard deviation of building height,  $h_i$  is the height of building  $i$ , and  $N$  is the total number of buildings in the area. The average building height weighted by building plan area was calculated using the following equation:

$$\bar{h}_{AW} = \frac{\sum_{i=1}^N A_i h_i}{\sum_{i=1}^N A_i} \quad (3)$$

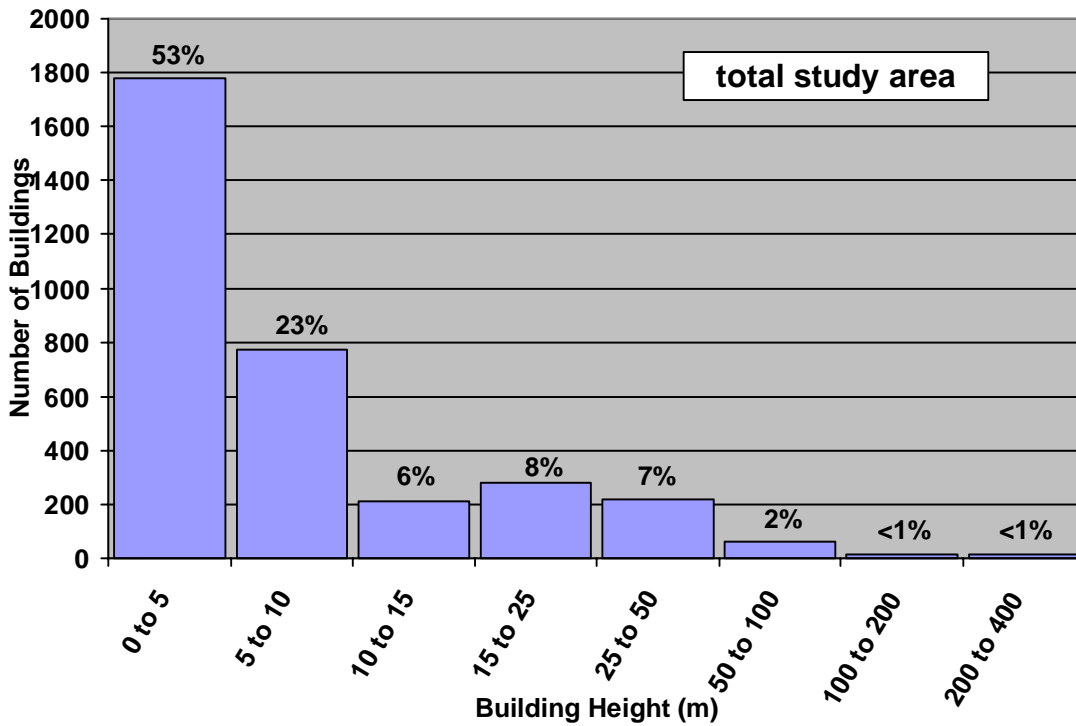
where  $\bar{h}_{AW}$  is the mean building height weighted by building plan area, and  $A_i$  is the plan area at ground level of building  $i$ .

*Results.* For the 12-km<sup>2</sup> domain, the mean building height based on Eqn. (1) was calculated to be 11.95 m and the standard deviation was calculated to be 22.7 m. The mean building height weighted by plan area was computed to be 17 m for the study area, indicating that taller buildings have greater plan area on average. The minimum and maximum building heights in the study area are 2.9 m and 331 m. Recall that the buildings we added to the study area were assigned a height of 4.0 meters if they appeared to be one story. Given the uncertainty of assigning height based on a digital orthophoto, the minimum building height may indeed (but

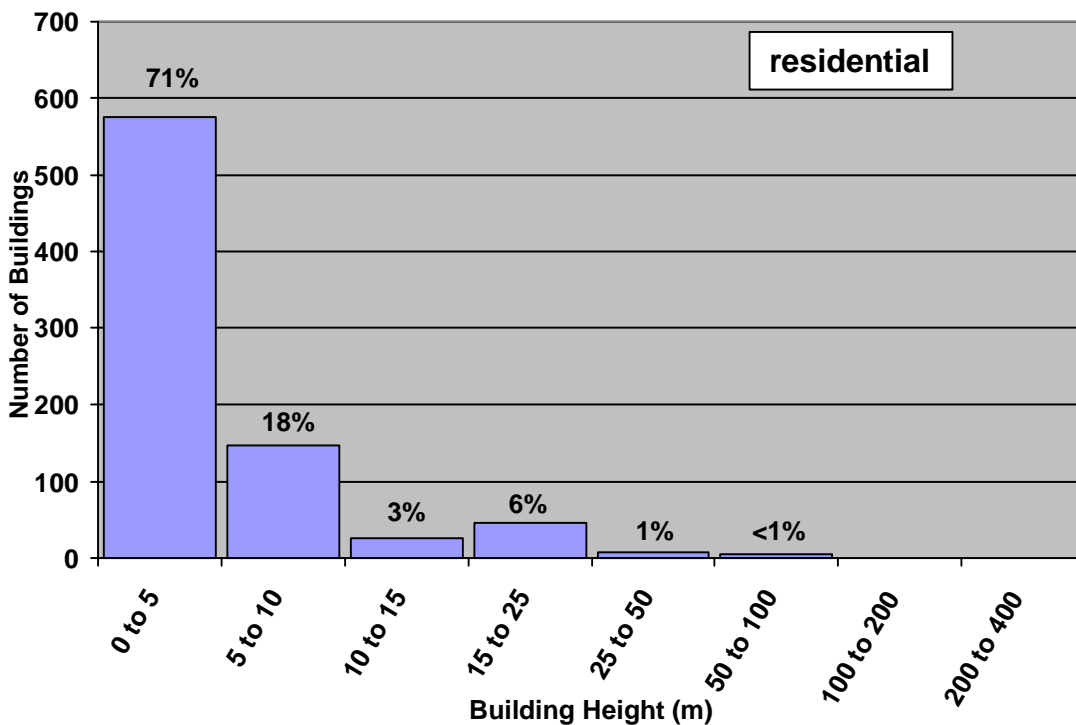
unlikely) be less than 2.9 m, although this is not considered important since the number of buildings in the study area that could be less than 2.9 m is low.

Figure 4 is a histogram of building heights for the study area. Note that the building height bin widths are not equal and grow in size with height. More than 75% of the buildings in the study area have heights of 10 meters or less (68% of the buildings shorter than 10 m were added to the database by us as described in Section 2). There are 31 buildings with heights greater than 100 meters, which amounts to less than 1% of the buildings in the study area. As noted in Section 2, the study area is predominantly Commercial & Services, Industrial, and High-density Single-family Residential land use. Next, we look at building height characteristics as a function of land use.

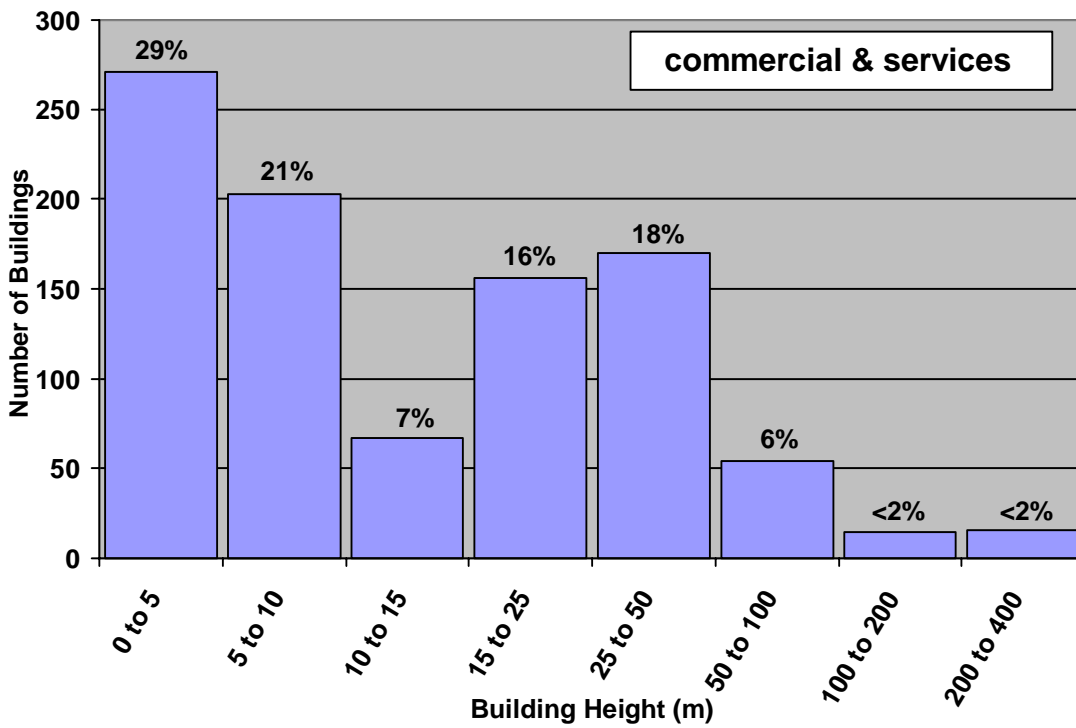
Figures 5, 6, 7, 8, 9, 10, and 11 show the building height histograms for the 7-category land use scheme: Residential, Commercial & Services, Industrial, Transportation/Communications/Utilities, Mixed Industrial & Commercial, Mixed Urban or Built-up, and Other Urban or Built-up. Figures 5 and 7 show that Residential and Industrial buildings are predominantly one or two story structures, with a few high-rise apartment buildings. Also note that 85% of the buildings in the Residential land use category were added to the original dataset. In the Commercial & Services land use category (Fig. 6) we observe a higher frequency of buildings with heights greater than 25 meters as compared to the other land uses, which is expected because it includes the downtown area with high rises. The buildings in the Mixed Industrial & Commercial land use category (Fig. 9) have a distribution very similar to the Industrial land use. The Mixed Urban or Built-up land use category (Fig. 10) has a building height distribution similar to the Commercial & Services land use category. Figures 8 and 11 indicate that Transportation/Communications/Utilities and Other Urban or Built-up contain few buildings.



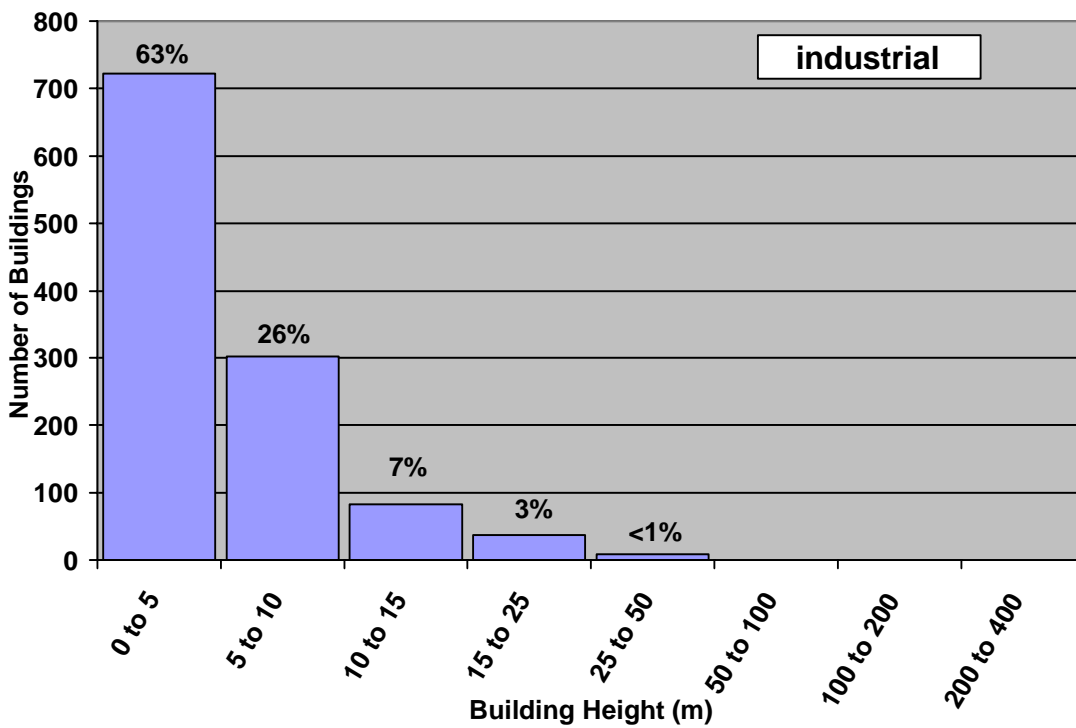
**Figure 4.** Distribution of building heights in the 12-km<sup>2</sup> downtown Los Angeles study area. The percent of buildings in each height category are shown above each bar in the chart.



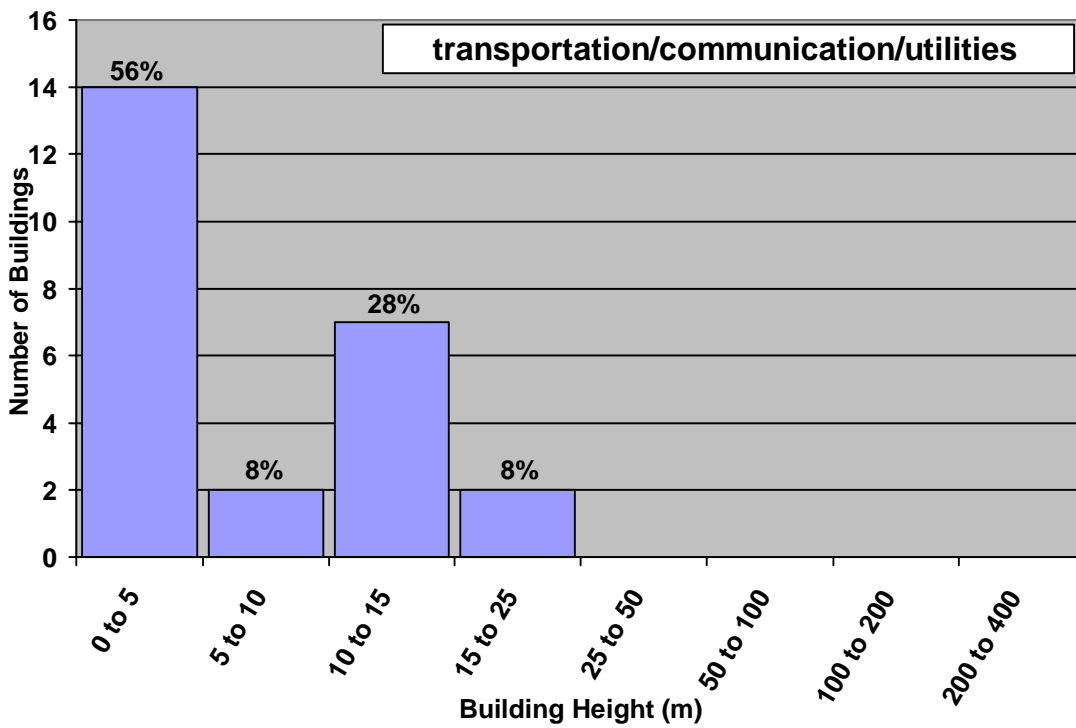
**Figure 5.** Distribution of building heights in the Residential land use category.



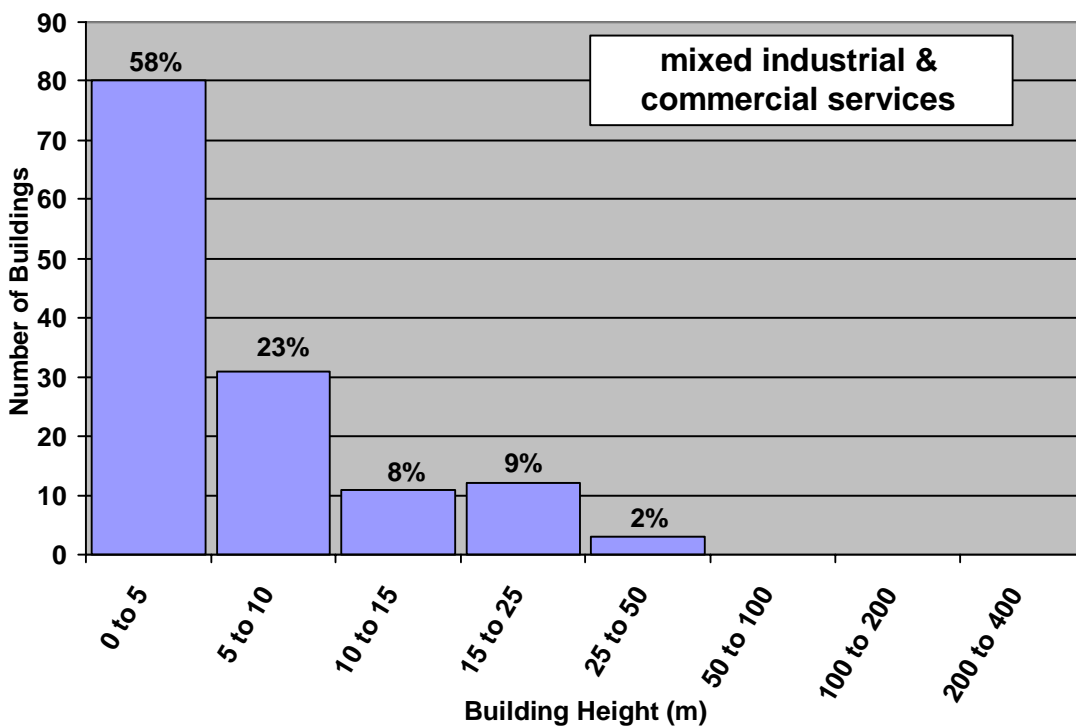
**Figure 6.** Distribution of building heights in the Commercial & Services land use category.



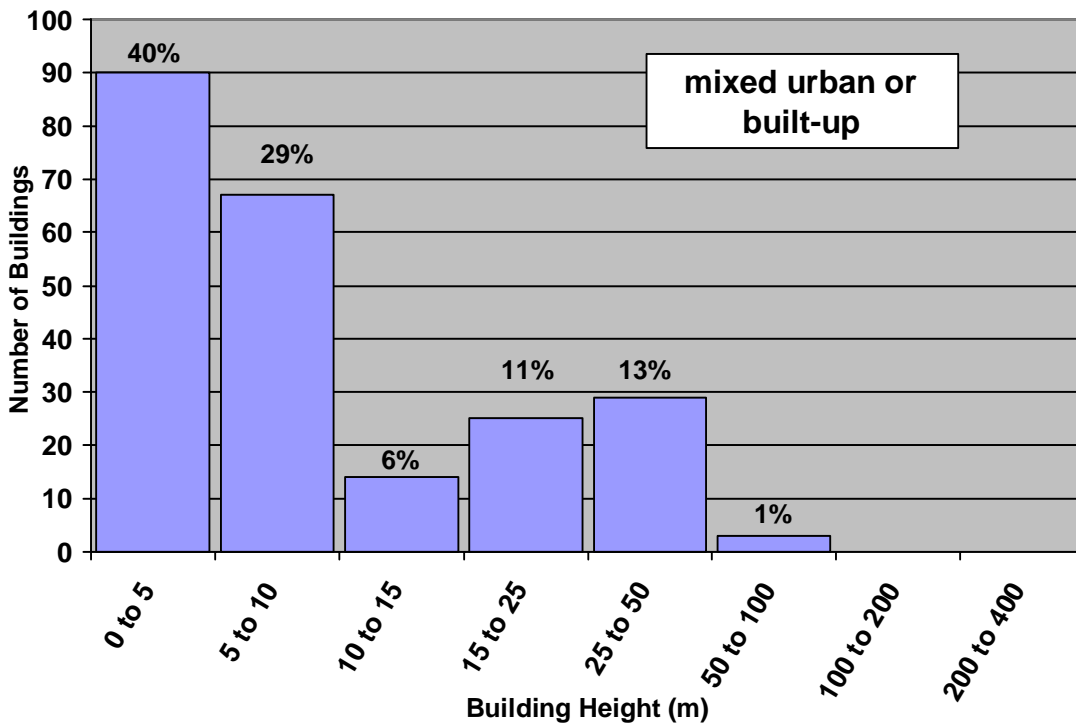
**Figure 7.** Distribution of building heights in the Industrial land use category.



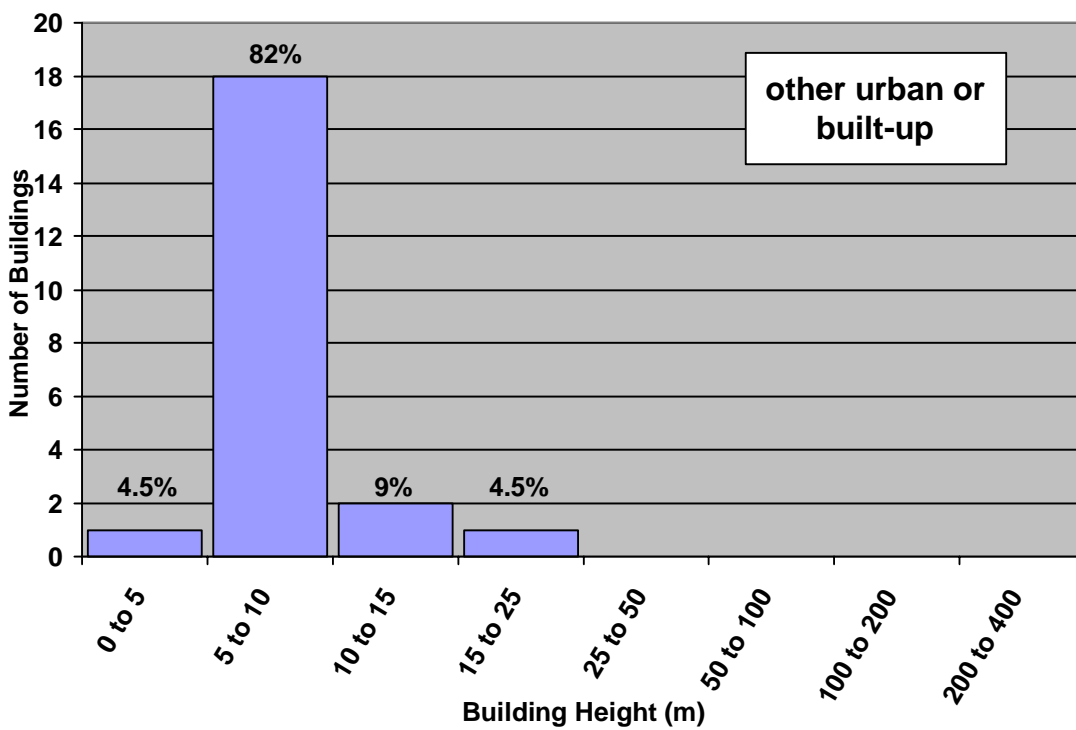
**Figure 8.** Distribution of building heights in the Transportation/Comm/Utilities land use category.



**Figure 9.** Distribution of building heights in the Mixed Industrial & Commercial land use category.

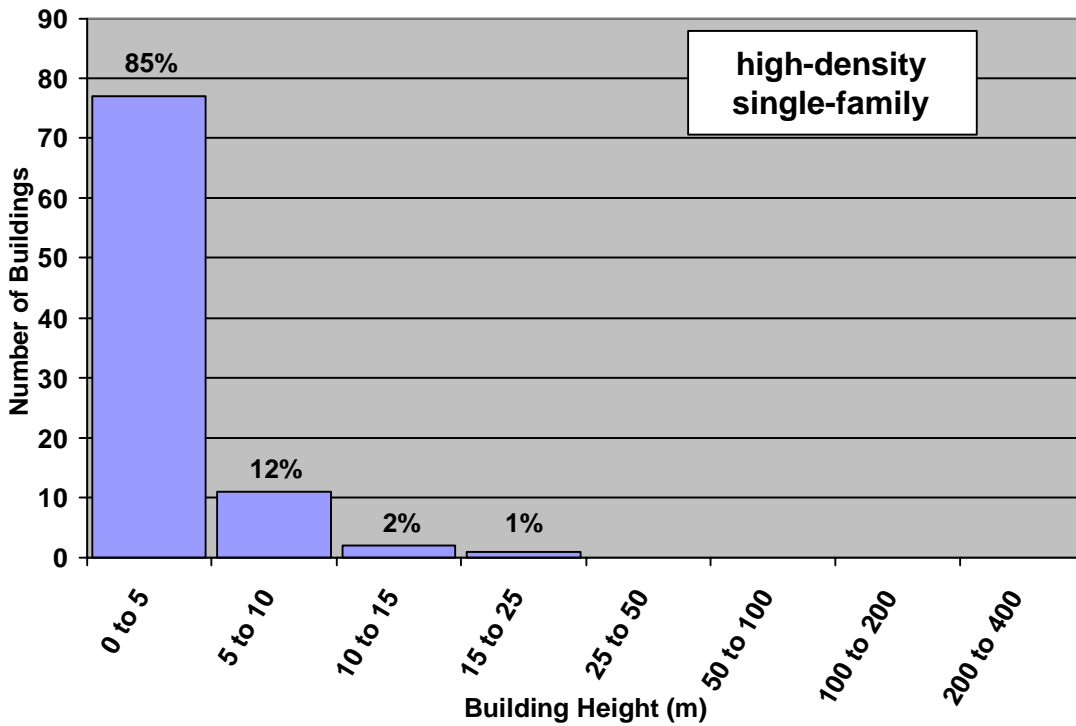


**Figure 10.** Distribution of building heights in the Mixed Urban or Built-up land use category.

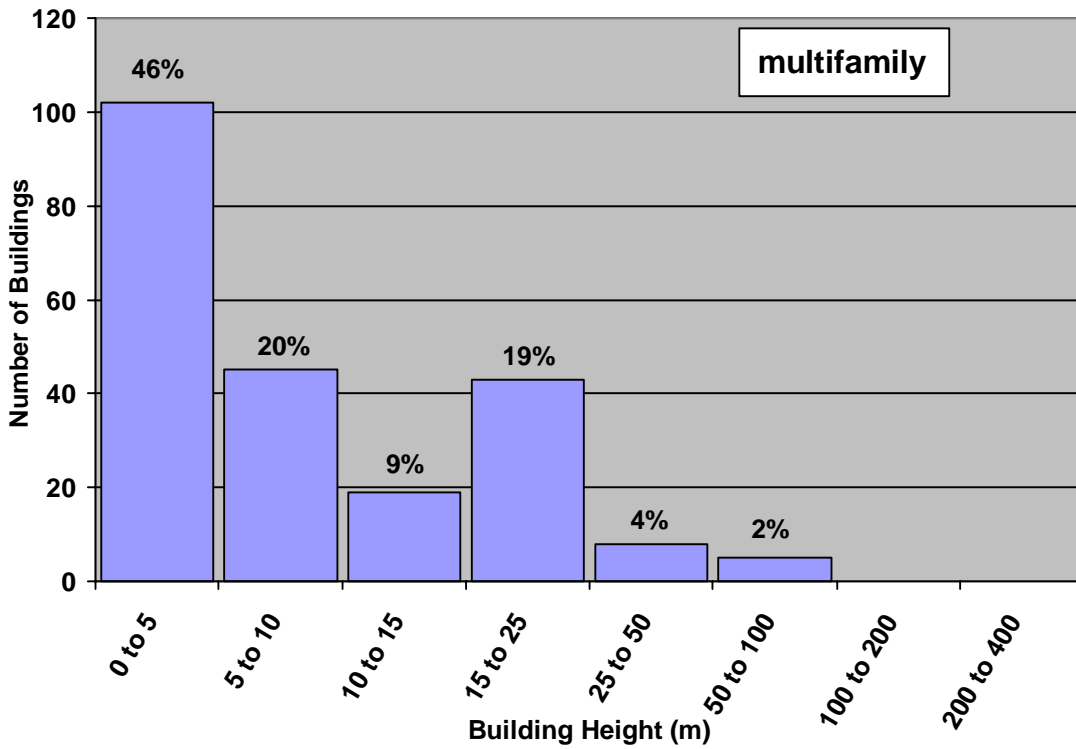


**Figure 11.** Distribution of building heights in the Other Urban or Built-up land use category.

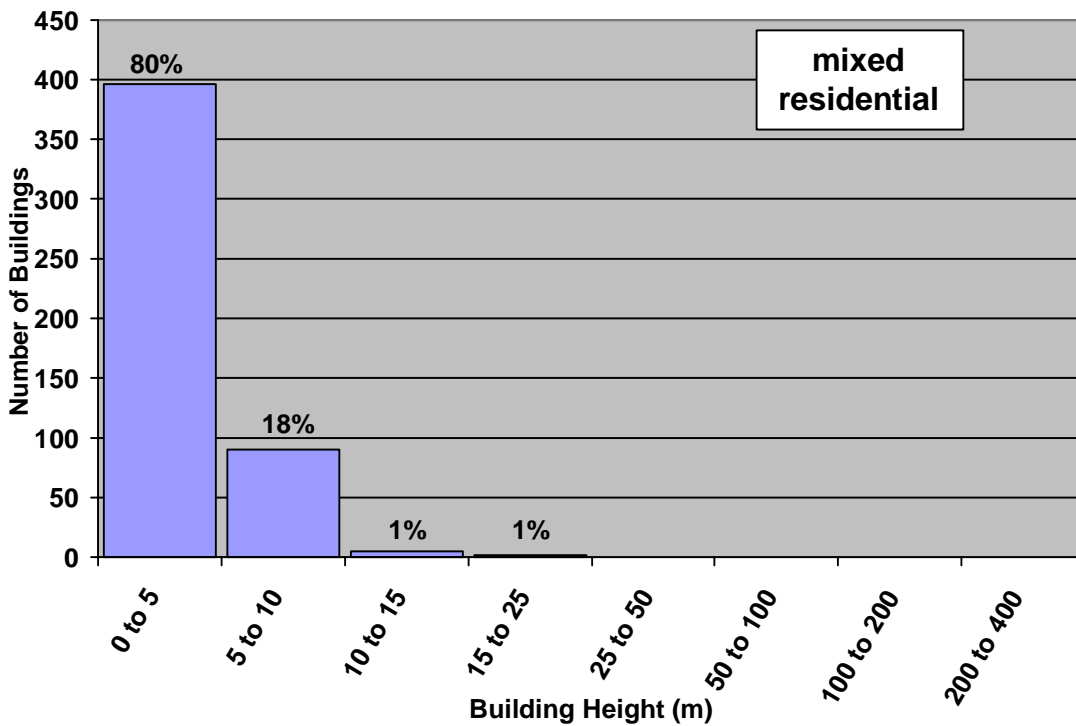
Figures 12, 13, and 14 show the building height histograms for three of the four sub-categories of Residential land use contained in the Los Angeles dataset (Low-density Single-family Residential land use is not found in the study area). The High-density Single-family Residential land use category has the same building height distribution as the Mixed Residential land use category. The Multifamily Residential land use category contains the high-rise apartment and condominium buildings; therefore, the building height distribution shows a number of buildings in the 15-25 meter height bin.



**Figure 12.** Distribution of building heights in the High-density Single-family Residential land use category.

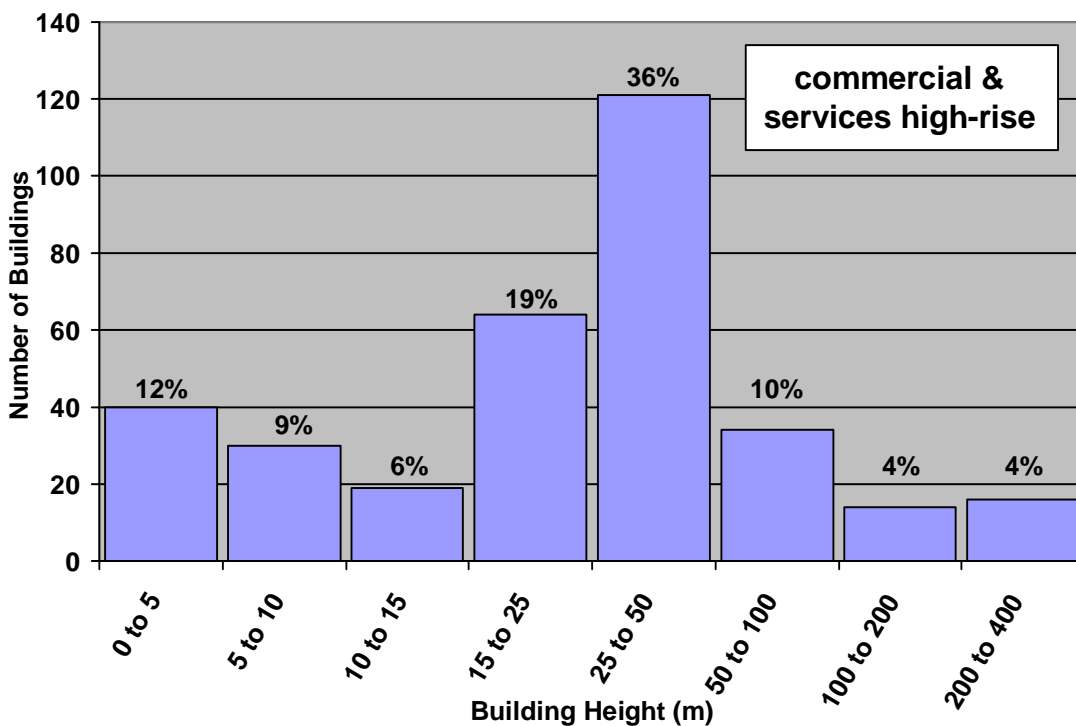


**Figure 13.** Distribution of building heights in the Multifamily Residential land use category.

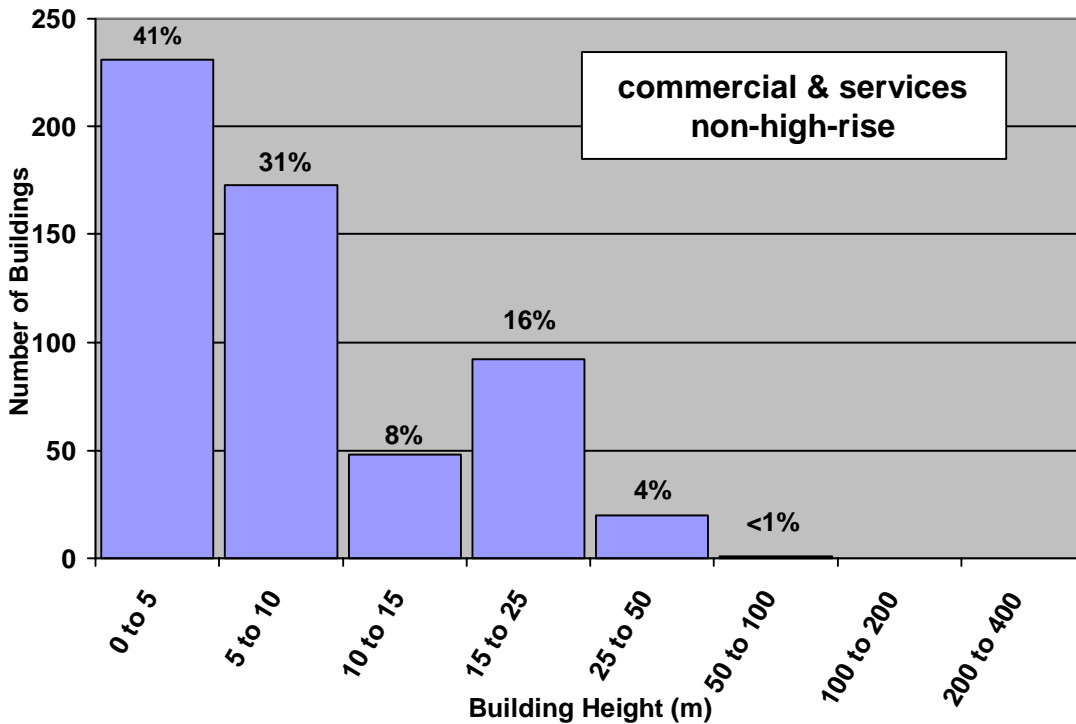


**Figure 14.** Distribution of building heights in the Mixed Residential land use category.

Figures 15 and 16 show the building height histograms for the two sub-categories of Commercial & Services land use: High-rise and Non-high rise. Clearly the Commercial & Services High-rise land use contains predominantly taller buildings, especially in the 25-50 m range. The buildings in the Commercial & Services Non-high-rise land use category are mostly shorter than 25 m.

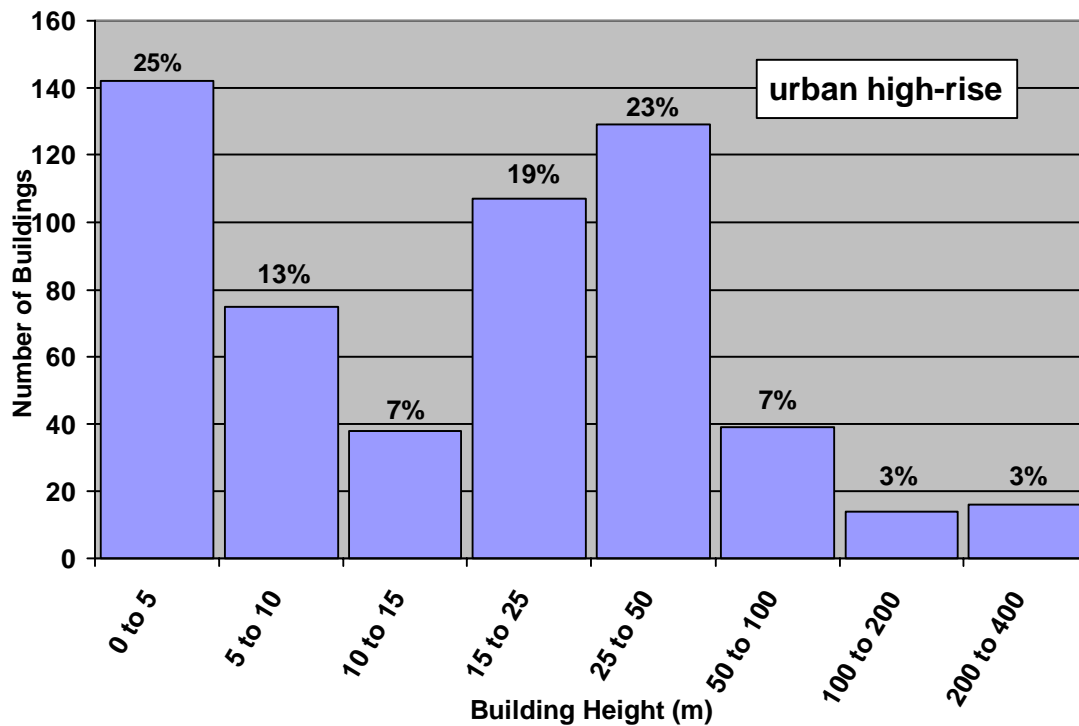


**Figure 15.** Distribution of building heights in the Commercial & Services High-rise.

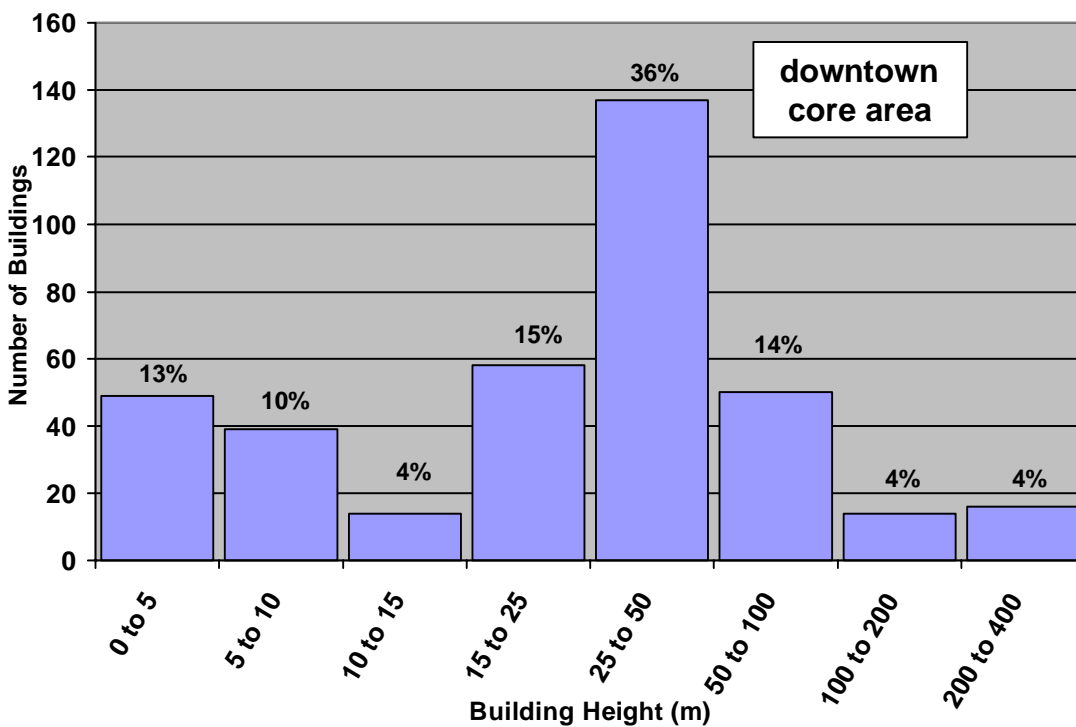


**Figure 16.** Distribution of building heights in the Commercial & Services Non-high-rise land use category.

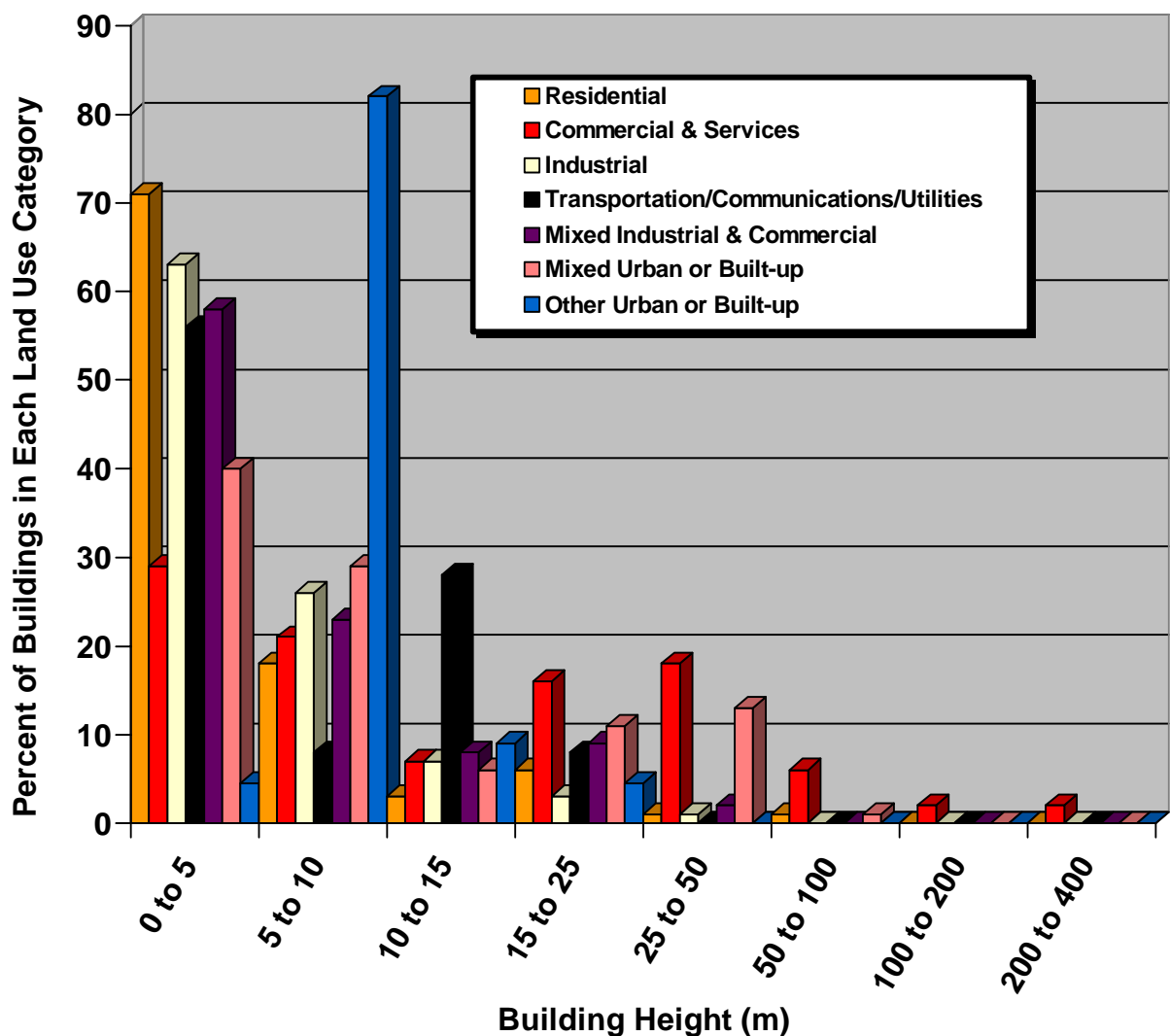
Figures 17 and 18 show the building height histograms for the Urban High-rise and the Downtown Core Area land uses. The Urban High-rise land use contains a mixture of short buildings and high-rises. This building height distribution can be partially explained by considering a city block that is classified as high-rise office. This block might contain a single high-rise building and be surrounded by several smaller buildings, i.e., the resolution of the land use data set (2500 m<sup>2</sup>) is such that several building types may reside in the same land use type. The Downtown Core Area is defined as the concentrated area of high-rise structures in the downtown area of a city, which is verified by the building height distribution shown in Figure 18.



**Figure 17.** Distribution of building heights in the Urban High-rise land use category.

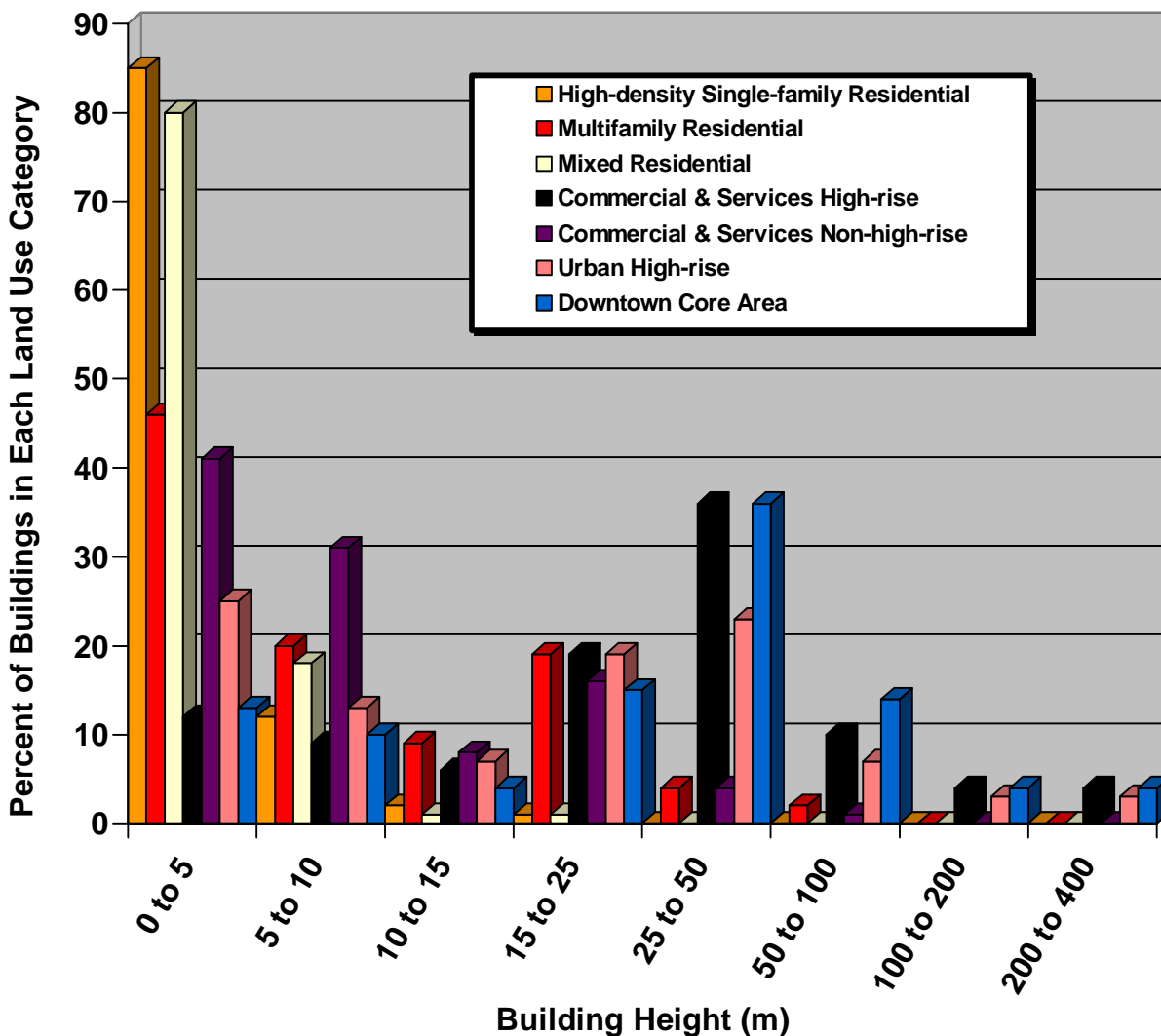


**Figure 18.** Distribution of building heights in the Downtown Core Area land use category.



**Figure 19.** Comparison of the percent of buildings in each height increment for each 7-category land use type.

Figure 19 displays in the same plot a comparison of building height histograms in percentage form for all 7 urban land use types in classification scheme 1. Figure 20 shows the height histogram comparison for the 12-category land use scheme and the Urban High-rise and Downtown Core Area land uses. One can better see in these plots the similarities (e.g., similarity between High-density Single-family Residential and Mixed Residential) and differences between different land use categories. Recall, however, that some of the land uses have significantly more buildings than others.



**Figure 20.** Comparison of the percent of buildings in each height increment for Residential and Commercial & Services sub-categories and the special High-rise land use types.

Table 3 summarizes the building height characteristics for the land use types used in the building analysis. Several interesting features stand out. The buildings in the Residential land use average between 1 to 2 stories in height, but when plan area-weighted the average building height is closer to 3 stories. This most likely indicates that multi-story apartment buildings with large footprints are significant in this land use category. This observation is supported by the statistics of the buildings in the Multifamily and Mixed Residential land use types. Table 3 also shows that the Industrial land use type is predominantly made up of shorter buildings (note the mean height of 6.3 m and the small standard deviation of 4.6 m), while Commercial & Services land use contains the taller buildings (mean height of 24.5 m and standard deviation of 38.5 m). The breakdown of Commercial & Services into High-rise and Non-high-rise categories shows that the average height of the Commercial & Services Non-high-rise is about 3-4 stories. The Mixed Industrial & Commercial land use type has characteristics more closely resembling the

Industrial land use type as compared to Commercial & Services. The buildings in the Urban High-rise area of Los Angeles have an average height of 31.6 m, and a high standard deviation of 46.5 m. The buildings in the Downtown Core Area, however, have an average height of 45.0 m, and a very high standard deviation of 53.2 m. The Urban High-rise land use category contains areas outside of the Downtown Core Area that have a mixture of shorter buildings adjacent to the high-rises.

**Table 3.** Summary of building characteristics for the downtown Los Angeles study area as a function of land use type.

Land Use Class	Number of Buildings	Average Height (m)	Standard Deviation	Plan Area-Weighted Average Height (m)
<b>Residential</b>	<b>806</b>	<b>6.4</b>	<b>6.9</b>	<b>10.4</b>
Low-density Single-family (< 8 units/hectare)	0	0	0	0
High-density Single-family ( $\geq 8$ units/hectare)	91	4.8	2.3	5.0
Multifamily	222	11.0	11.6	16.6
Mixed	493	4.7	1.6	4.9
<b>Commercial &amp; Services</b>	<b>952</b>	<b>24.5</b>	<b>38.5</b>	<b>28.9</b>
Non-high-rise	614	13.2	16.4	17.9
High-rise	338	45.1	55.2	48.7
<b>Industrial</b>	<b>1154</b>	<b>6.3</b>	<b>4.6</b>	<b>7.3</b>
<b>Transportation/Communications/Utilities</b>	<b>25</b>	<b>7.9</b>	<b>5.0</b>	<b>9.4</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>137</b>	<b>7.5</b>	<b>6.4</b>	<b>8.7</b>
<b>Mixed Urban or Built-up</b>	<b>228</b>	<b>12.0</b>	<b>11.9</b>	<b>18.1</b>
<b>Other Urban or Built-up</b>	<b>22</b>	<b>7.4</b>	<b>4.2</b>	<b>13.8</b>
Predominantly Vegetated	18	6.4	1.5	7.7
Predominantly Built-up	4	11.7	9.1	18.1
<b>Urban High-rise</b>	<b>560</b>	<b>31.6</b>	<b>46.5</b>	<b>42.6</b>
<b>Downtown Core Area</b>	<b>377</b>	<b>45.0</b>	<b>53.2</b>	<b>44.1</b>

In the next nine sub-sections, we calculate the building plan area fraction ( $\lambda_p$ ), building area density ( $a_p(z)$ ), rooftop area density ( $a_r(z)$ ), frontal area index ( $\lambda_F$ ), frontal area density ( $a_F(z)$ ), complete aspect ratio ( $\lambda_C$ ), building surface area to plan area ratio ( $\lambda_B$ ), height-to-width ratio ( $\lambda_S$ ), the roughness length ( $z_o$ ), and the displacement height ( $z_d$ ). The calculation procedures and results are summarized in each sub-section.

### 3.2 Building Plan Area Fraction ( $\lambda_p$ )

Building plan area fraction has been shown to be related to the surface roughness  $z_o$  (see Section 3.10). Surface roughness is used in air quality and meteorological models to account for enhanced mixing and drag effects of the rough surface. In the urban context, as the density of buildings (plan area fraction) increases so does the roughness of the system, but a threshold is eventually reached where adding new elements effectively reduces the drag of the elements present (Grimmond and Oke 1999). The density of buildings also indicates the potential flow regime. Hussain and Lee (1980) performed wind-tunnel experiments and found that three flow regimes develop in idealized urban street canyons: (1) isolated flow, (2) wake interference flow, and (3) skimming flow. The isolated flow regime occurs when elements are spaced relatively far apart ( $0 < \lambda_p < 0.1$ ), the wake interference flow occurs when elements are spaced at a medium density level ( $0.1 < \lambda_p < 0.6$ ), and the skimming flow regime occurs for high-density building arrangements ( $\lambda_p > 0.6$ ) (Oke 1988).

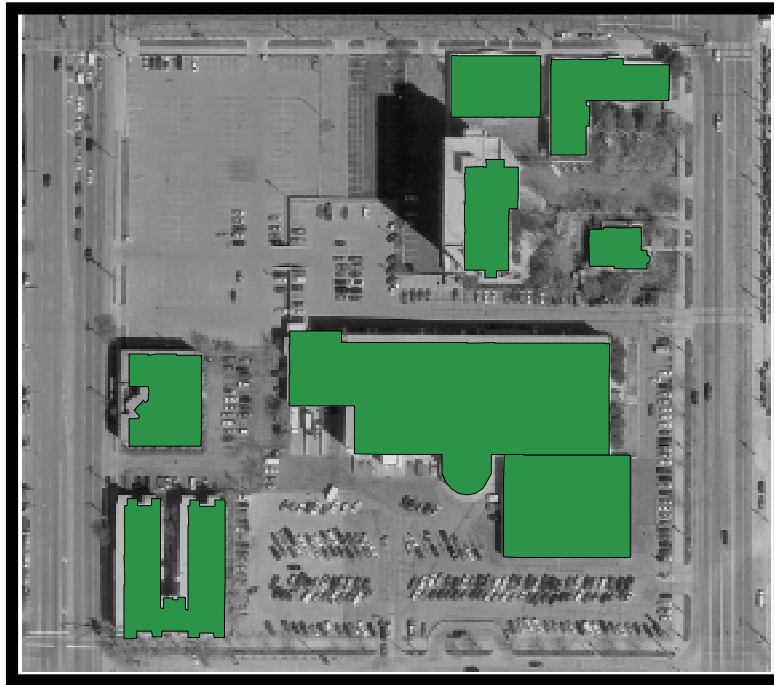
The building plan area fraction ( $\lambda_p$ ) is defined as the ratio of the plan area of buildings to the total surface area of the study region:

$$\lambda_p = \frac{A_p}{A_T} \quad (4)$$

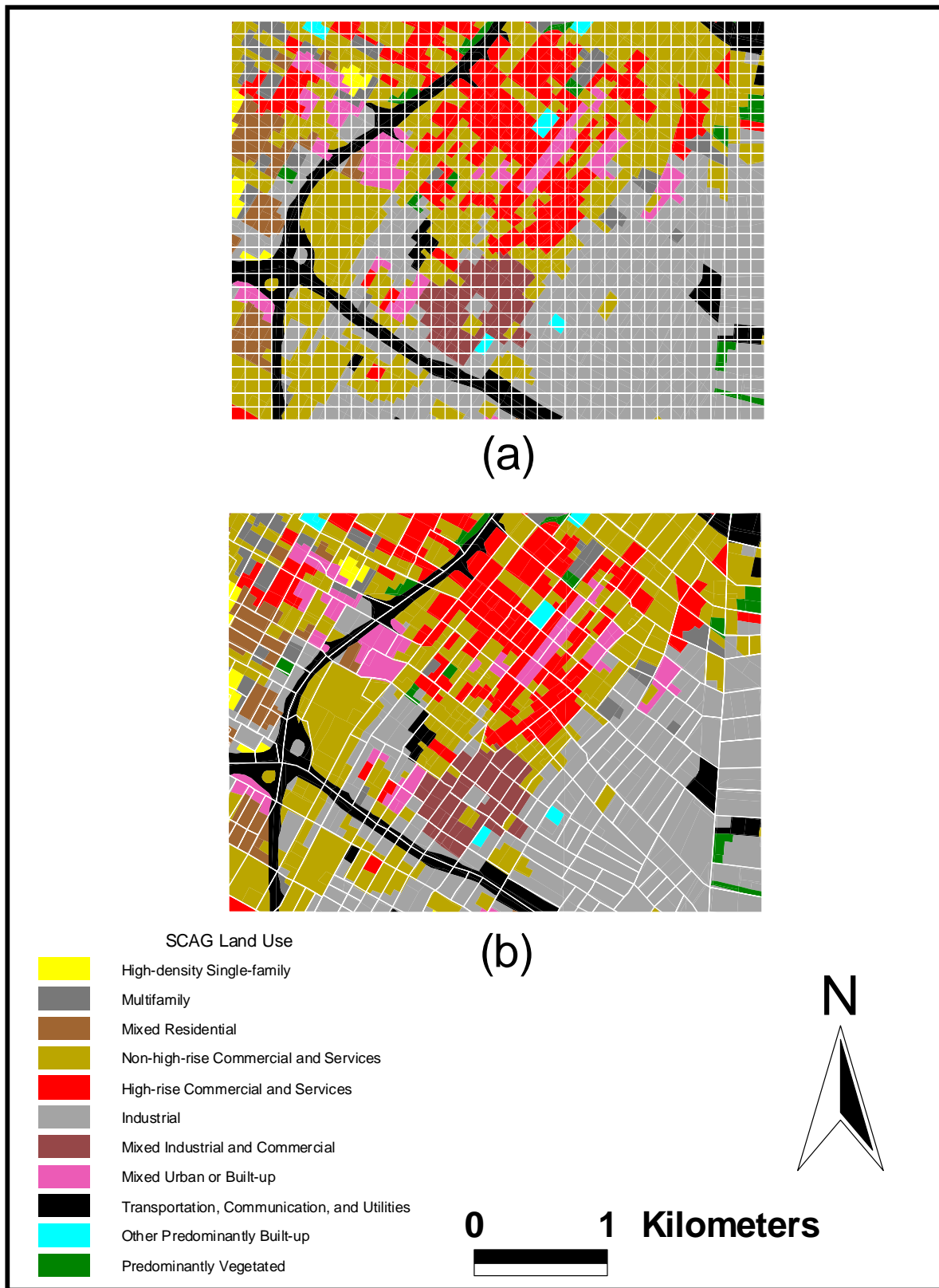
where  $A_p$  is the plan area of buildings at ground level, i.e., the footprint area, and  $A_T$  is the total plan area of the region of interest, i.e., an arbitrary area that encompasses the buildings (see Figure 21). The computed value of the plan area fraction is dependent on the size of the area or the specific area in a city selected for the calculation. In most cases the plan area fraction will vary significantly from one city block to the next because of the heterogeneous nature of the urban landscape. The appropriate size of the calculation element should be chosen such that the characteristics of interest in the urban area are discernible.

*Results.* For the 12-km<sup>2</sup> study area the plan area fraction at ground level was calculated to be 0.30. This value is significantly lower than the plan area fraction of 0.47 found for Mexico City, Mexico (Grimmond and Oke 1999) and is slightly lower than the 0.37 found for Vancouver, British Columbia, Canada (Voogt and Oke 1997).

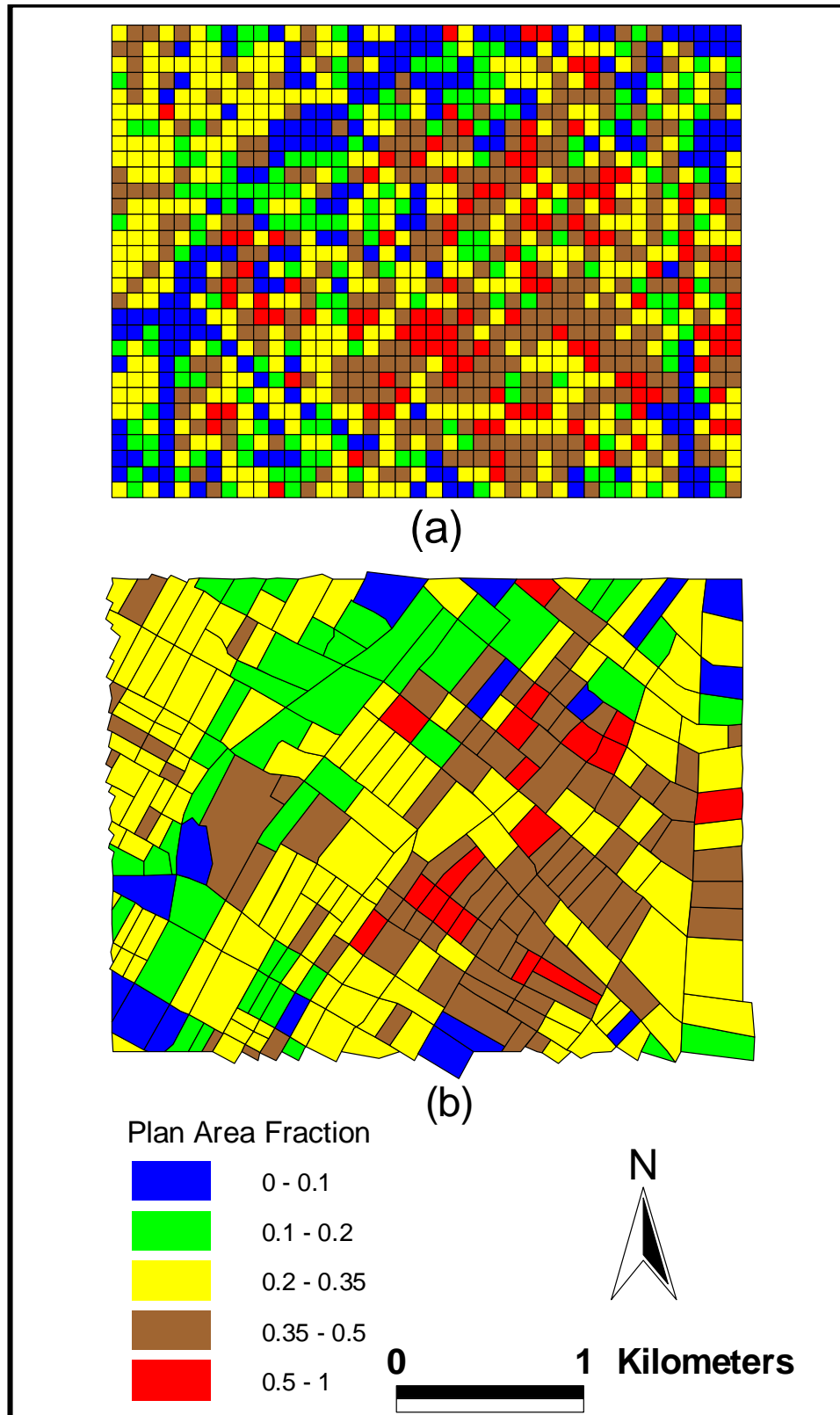
We have calculated the plan area fraction on two meshes overlaid onto the study area in order to view the spatial heterogeneity. Figure 22 shows the two meshes overlaid onto land use: in the first case, a uniform 100-m X 100-m rectilinear grid cell mesh covering the entire 12-km<sup>2</sup> study area, and in the second case a non-uniform polygonal grid cell mesh based on the street network. As can be seen, the polygonal grids somewhat coincide with underlying land use type. Figure 23 shows the plan area fraction according to the two grid cell meshes. It is clear by comparison that there is significant variation within the polygonal meshes that follow the street network. The major highways running through the study area are clearly visible on the uniform mesh as open areas (low values of  $\lambda_p$ ). It is more difficult to see a one-to-one correlation with urban land use type, i.e., there appears to be significant variation in  $\lambda_p$  within an urban land use type. For example, in the industrial area in the southeast (gray region, Fig. 22), the plan area fraction ranges from high density to relatively open areas (Fig. 23).



**Figure 21.** Illustration of building plan area fraction. The building plan area ( $A_p$ ) in this scene is the sum of the areas of the building footprints shown in green. The total plan area ( $A_T$ ) is the area enclosed by the outline of the figure. The building plan area fraction ( $\lambda_p$ ) is computed by dividing building plan area ( $A_p$ ) by total plan area ( $A_T$ ).



**Figure 22.** Grid cells used to display and analyze the spatial heterogeneity of the Los Angeles building morphology for the 12-km<sup>2</sup> study area. Urban land use type overlaid with (a) the 100-m X 100-m uniform grid cell mesh, and (b) the non-uniform grid cells based on street network.



**Figure 23.** Spatial variability of building plan area fraction ( $\lambda_p$ ) distributed according to a uniform 100-m X 100-m grid mesh and a non-uniform grid mesh based on the downtown road network.

Table 4 contains the computed  $\lambda_p$  for each land use type in the land use classification schemes described in Section 2.2. Table 4 indicates that the Mixed Industrial & Commercial land use category is significantly higher than the other land use types. The Industrial land use has a higher building density than the Commercial & Services land use. The Transportation/Communications/Utilities and Other Urban or Built-up land uses contain only a few buildings and hence have a low plan area fraction. Surprisingly, the plan area fraction for the Residential areas is nearly the same as the Commercial & Services land use type, but one should recall that in our study area all Residential land use is high density. Most of the average values shown in Table 4 fall within the  $\lambda_p$  range for wake interference flow ( $0.1 < \lambda_p < 0.6$ ) by Oke (1988).

**Table 4.** Plan area fraction as a function of land use type

Land Use Class	$\lambda_p$
<b>Residential</b>	<b>0.30</b>
Low-density Single-family (< 8 units/hectare)	---
High-density Single-family ( $\geq 8$ units/hectare)	0.27
Multifamily	0.31
Mixed	0.29
<b>Commercial &amp; Services</b>	<b>0.28</b>
Non-high-rise	0.26
High-rise	0.32
<b>Industrial</b>	<b>0.38</b>
<b>Transportation/Communications/Utilities</b>	<b>0.03</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>0.47</b>
<b>Mixed Urban or Built-up</b>	<b>0.34</b>
<b>Other Urban or Built-up</b>	<b>0.06</b>
Predominantly Vegetated	0.05
Predominantly Built-up	0.13
<b>Urban High-rise</b>	<b>0.32</b>
<b>Downtown Core Area</b>	<b>0.29</b>

In Table 5, we compare the computed plan area fraction values for several land use types in Los Angeles to those reported in other studies. Our computed values of  $\lambda_p$  for Residential and Downtown Core Area are smaller than those of other cities, while our Industrial value is nearly the same as that measured in Vancouver, BC. The plan area fraction values computed in these other studies have included the plan area of trees in residential areas, which can be a significant fraction of the plan area. Trees are not included in our calculations of  $\lambda_p$  and explain some of the differences. However, visual inspection of aerial photos suggests that there are relatively few trees and shrubs in the high-density residential areas in our study region. We suspect that the relatively low values of  $\lambda_p$  are also due to the wide streets and large parking areas associated with the high-density residential apartment complexes. The relatively low values for the Los Angeles downtown area can be attributed to the small footprint of the downtown core area high rises and the large amount of car habitat (e.g., roadways, parking lots, driveways) present in the

downtown Los Angeles area, which effectively limits the amount of buildings and minimizes the open space available for trees and shrubs.

**Table 5.** Comparison of plan area fraction ( $\lambda_p$ ) for downtown Los Angeles to other cities. Locations grouped by land use type and then listed in order of decreasing  $\lambda_p$ .

Location	Land Use Class	$\lambda_p$	Source
Vancouver, BC, Canada	Suburban Residential	0.62	Voogt and Oke (1997)
Sacramento, CA	Suburban Residential	0.58	Grimmond and Oke (1999)
Arcadia, CA	Suburban Residential	0.53	Grimmond and Oke (1999)
Chicago, IL	Suburban Residential #1	0.47	Grimmond and Oke (1999)
Chicago, IL	Suburban Residential #2	0.38	Grimmond and Oke (1999)
San Gabriel, CA	Suburban Residential	0.36	Grimmond and Oke (1999)
Miami, FL	Suburban Residential	0.35	Grimmond and Oke (1999)
Tucson, AZ	Suburban Residential	0.33	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Mixed Residential</b>	<b>0.29</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>High-density Single-family Residential</b>	<b>0.27</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>Industrial</b>	<b>0.38</b>	<b>This report</b>
Vancouver, BC, Canada	Light Industrial	0.38	Voogt and Oke (1997)
Mexico City, Mexico	Downtown	0.47	Grimmond and Oke (1999)
Vancouver, BC, Canada	Downtown	0.37	Voogt and Oke (1997)
<b>Los Angeles, CA</b>	<b>Urban High-rise</b>	<b>0.32</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>Downtown Core Area</b>	<b>0.29</b>	<b>This report</b>

### 3.3 Building Plan Area Density ( $a_p(z)$ )

The building plan area density gives information on how much of the air volume is occupied by buildings (when multiplied by the height increment of the volume of interest). The change in building plan area density with height yields the roof fraction (see Section 3.4). The roof fraction is important from a thermodynamic perspective because of the significant solar gain and heat loss there. The building plan area density can be used to derive the roof area density, which is analogous to the leaf area density. The leaf area density gives information on how much long- and shortwave radiation travels through the canopy and how much is intercepted. Something similar might be done for urban areas with buildings using the building plan area density. Building plan area density can also be used as a surrogate for frontal area density (see Section 3.5) in evaluating the drag force as a function of height due to buildings in urban areas.

The building plan area density ( $a_p(z)$ ) is defined as the average building plan area within a height increment divided by the volume of the height increment:

$$a_p(z) = \frac{\frac{1}{\Delta z} \int_{z - \frac{1}{2}\Delta z}^{z + \frac{1}{2}\Delta z} A_p(z') dz'}{A_T \Delta z} \quad (5)$$

where,  $A_p(z')$  is the plan area of buildings at height  $z'$ ,  $A_T$  is the plan area of the site, and  $\Delta z$  is the height increment for the calculation. Since  $A_T$  is not a function of height we can bring it into the integral in the numerator and obtain:

$$a_p(z) = \frac{\frac{1}{\Delta z} \int_{z - \frac{1}{2}\Delta z}^{z + \frac{1}{2}\Delta z} \frac{A_p(z')}{A_T} dz'}{\Delta z} \quad (6)$$

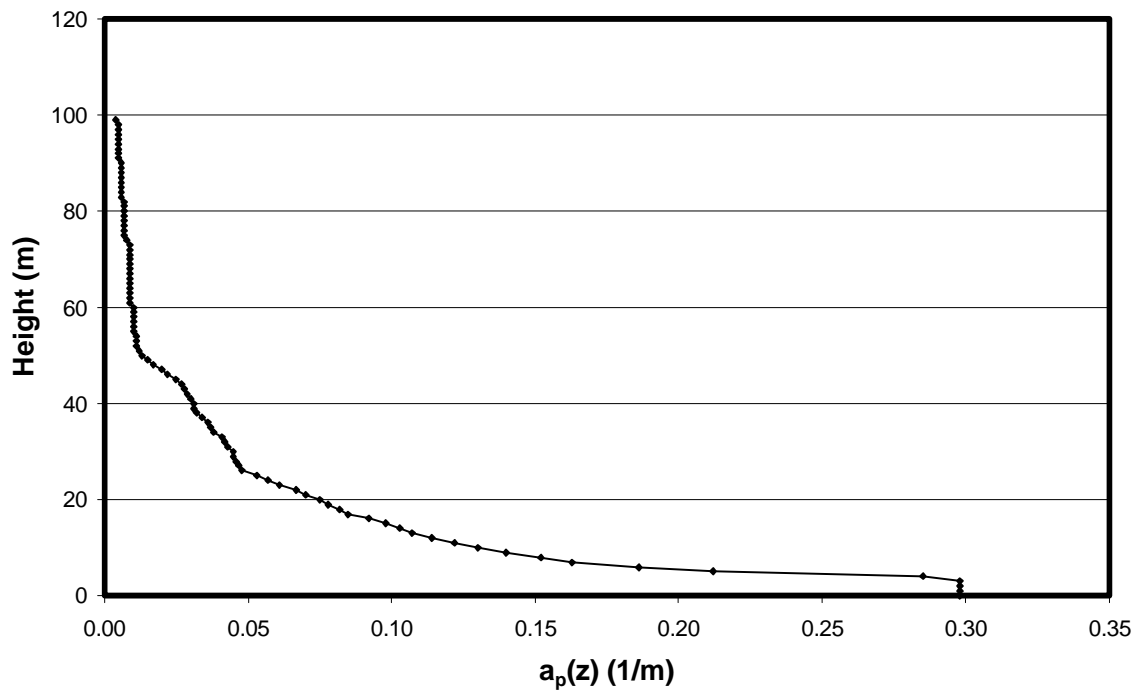
Knowing  $\lambda_p(z') = A_p(z')/A_T$  and assuming that the building plan area does not change appreciably within a height increment  $\Delta z$ , eq. (6) can be approximated by:

$$a_p(z) \cong \frac{\lambda_p(z)}{\Delta z} \quad (7)$$

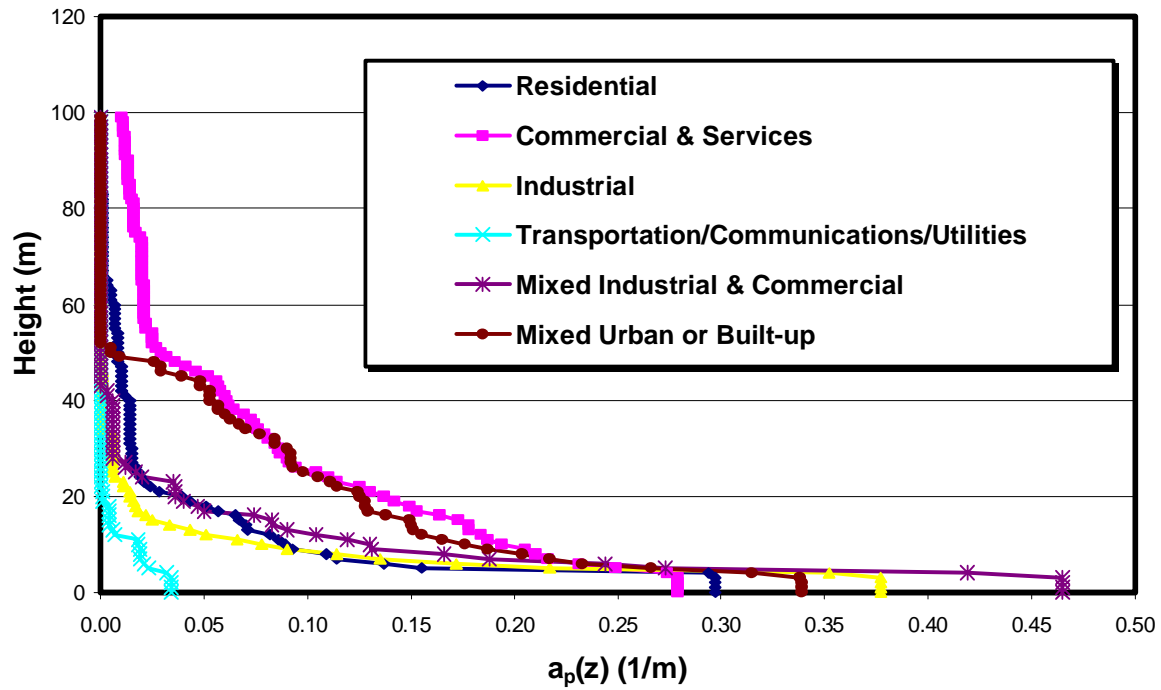
*Results.* Figure 24 illustrates the building plan area density function ( $a_p(z)$ ) for the Los Angeles study area using a 1-m height increment. As expected,  $a_p(z)$  is constant for the first few meters above ground elevation until the rooftop height of the shortest buildings are reached

(approximately four meters). Building plan area density then rapidly declines with height and asymptotically approaches  $\lambda_p = 0$ . Only the first 100 m above ground elevation are shown because  $a_p(z)$  is nearly zero above this height.

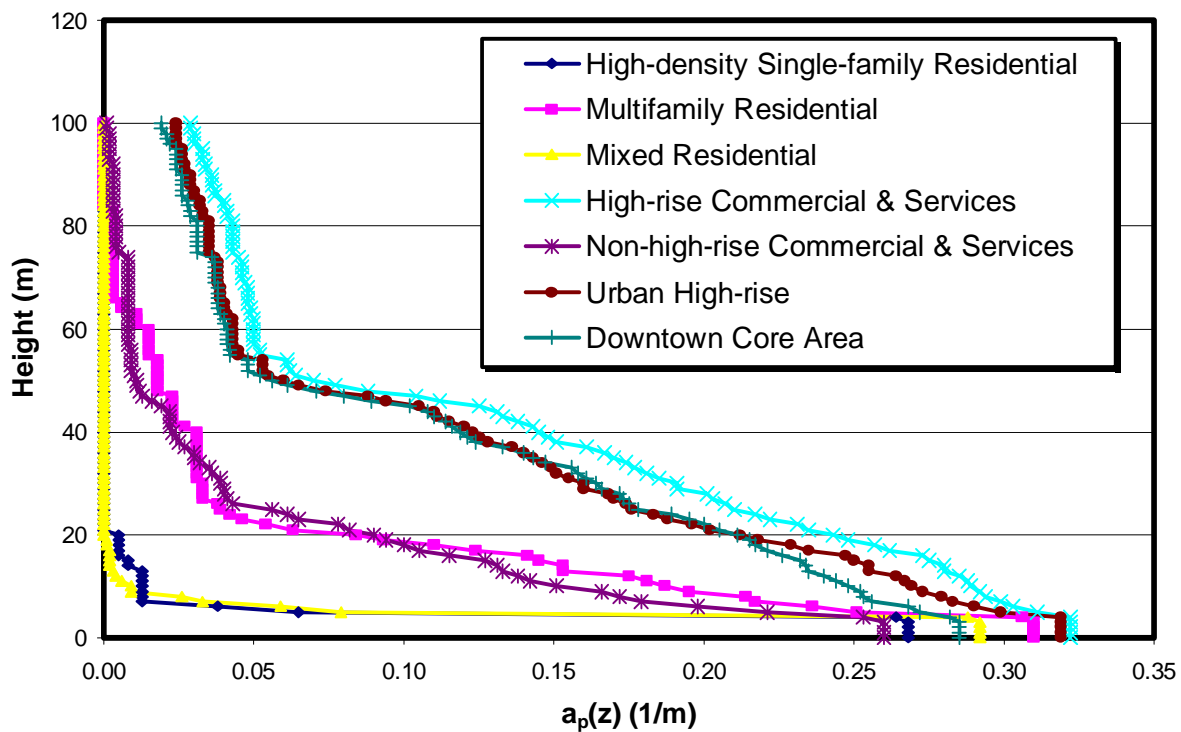
Figure 25 shows  $a_p(z)$  for the 7-category land use scheme. The plot does not contain the building plan area density for the Other Urban or Built-up land use because this land use does not contain enough buildings to produce meaningful results. The building plan area density of the Mixed Industrial & Commercial, Industrial, and Residential land uses decreases relatively rapidly with height above four meters, indicating that these land use categories do not contain many tall buildings. The  $a_p(z)$  for the Mixed Industrial & Commercial land use is the largest near the ground, indicating that the buildings in this land use type have a large footprint, but are short. Figure 26 shows  $a_p(z)$  for several land use types in the 12-category scheme, as well as the Urban High-rise and Downtown Core Area land uses. The plot shows that the  $a_p(z)$  associated with Commercial & Services Non-high-rise decreases much more rapidly with height than the Commercial & Services High-rise land use type and is very similar in nature to the Multifamily Residential. It is clear that the Commercial & Services land use type (found in the USGS LULC database) is composed of two distinct classes of buildings.



**Figure 24.** Building plan area density function ( $a_p(z)$ ) for the entire 12-km<sup>2</sup> downtown Los Angeles study area.



**Figure 25.** Building plan area density function ( $a_p(z)$ ) for six of the land use classes in the 7-category classification scheme.



**Figure 26.** Building plan area density function ( $a_p(z)$ ) for several land use types in the 12-category scheme and the Urban High-rise and Downtown Core Area land uses.

### 3.4 Roof Area Density ( $a_r(z)$ )

The rooftop area as a function of a height is important in describing the thermodynamics of the urban canopy. Roofs are interceptors and reflectors of solar radiation, and give off or absorb longwave radiation. Knowledge of the roof area, therefore, is important in determining the energy balance within the urban canopy. The roof area density is a quantity that can be used to compute roof area as a function of height. The roof area density is analogous to the leaf area density. The leaf area density can be integrated from the top of the vegetative canopy to the ground to yield a leaf area index. The leaf area index gives information on how much long- and shortwave radiation travels through the canopy and how much is intercepted. Roof area density might be used in a similar fashion to help estimate energy fluxes through the urban canopy.

The rooftop area within a height increment  $\Delta z$  can be approximated by the difference between the building plan areas at two heights:

$$A_r(z) = A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right) \quad (8)$$

where  $A_p(z)$  is the plan area of buildings at the specified height and a flat-roofed assumption has been made. The roof area density ( $a_r(z)$ ) can then be defined as the rooftop plan area per height increment  $\Delta z$  divided by the volume of the height increment:

$$a_r(z) = \frac{A_r(z)}{A_T \cdot \Delta z} = \frac{A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right)}{A_T \cdot \Delta z} \quad (9)$$

where  $A_T$  is the total area within which buildings are contained. Analogous to the leaf area index used in the plant canopy community, the integration of  $a_r(z)$  from a specified elevation above ground ( $z$ ) to the height of the canopy ( $h_c$ ) is equal to the building area index ( $L(z)$ ):

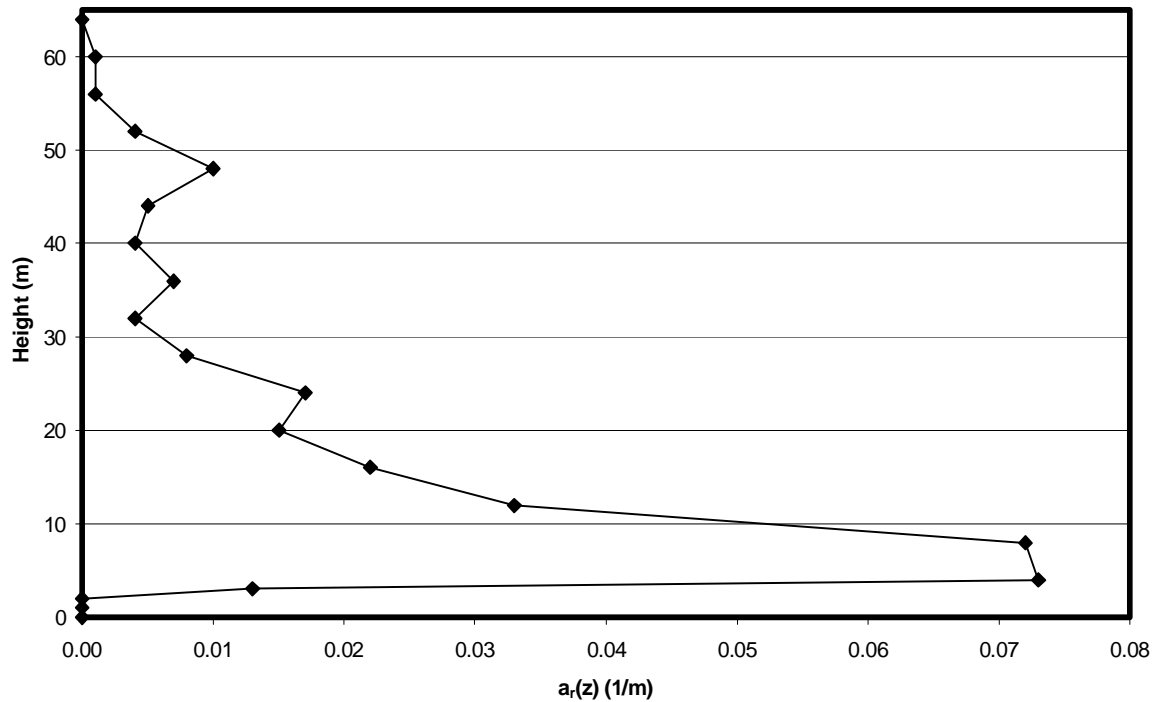
$$L(z) = \int_z^{h_c} a_r(z') dz' \quad (10)$$

The integration of  $a_r(z)$  from ground elevation to the canopy height ( $h_c$ ) is equal to  $\lambda_p$ :

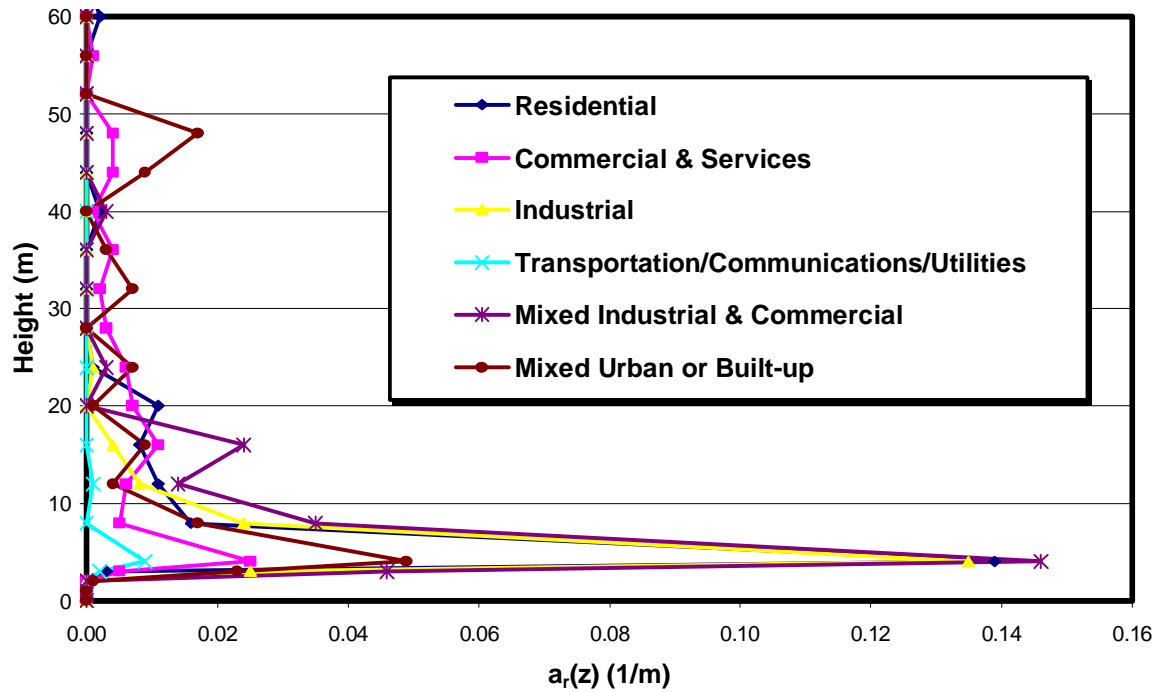
$$L(0) = \lambda_p = \int_0^{h_c} a_r(z') dz' \quad (11)$$

*Results.* The roof area density function  $a_r(z)$  is shown in Figure 27 for the Los Angeles study area. A significant fraction of the rooftop area is located within the first 10 meters of height above ground. The value of  $a_r(z)$  is zero below 4 m because no buildings are defined to be below 4 meters (one story) in height. Figures 28 and 29 show  $a_r(z)$  for the 7-category land use scheme and for the 12-category scheme along with the Urban High-rise and Downtown Core Area land use types, respectively. Each of the plots is limited to the first 65 meters of height to make them more readable because for most of the land use types the first 50 meters of height contains all the

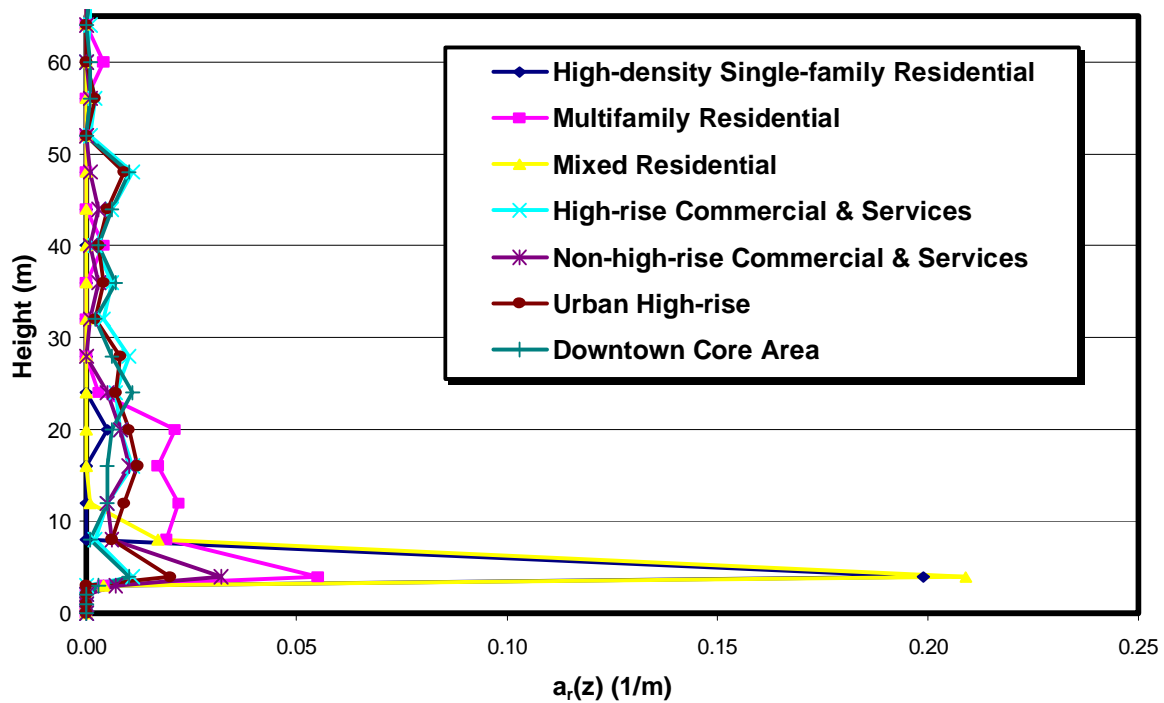
rooftop area. The Residential and Industrial land uses consistently have the largest rooftop density fraction within 5-10 meters of the ground, whereas the Commercial & Services Non-high-rise land use and the Urban High-rise generally have a more consistent distribution of roof area density at low heights continuing to 50 to 60 meters.



**Figure 27.** Roof area density function ( $a_r(z)$ ) for the Los Angeles study area. Data are plotted for 1-m height increments up to 4 m and then by 4-m increments (representing one story) up to 65 m.



**Figure 28.** Roof area density function ( $a_r(z)$ ) for the 7-category land use scheme. Data are plotted for 1-m height increments up to 4 m and then by 4-m increments (representing one story) up to 65m.



**Figure 29.** Roof area density function ( $a_r(z)$ ) for the 12-category land use scheme and the Urban High-rise and Downtown Core Area land use types. Data are plotted for 1-m height increments up to 4 m and then by 4-m increments (representing one story) up to 65m.

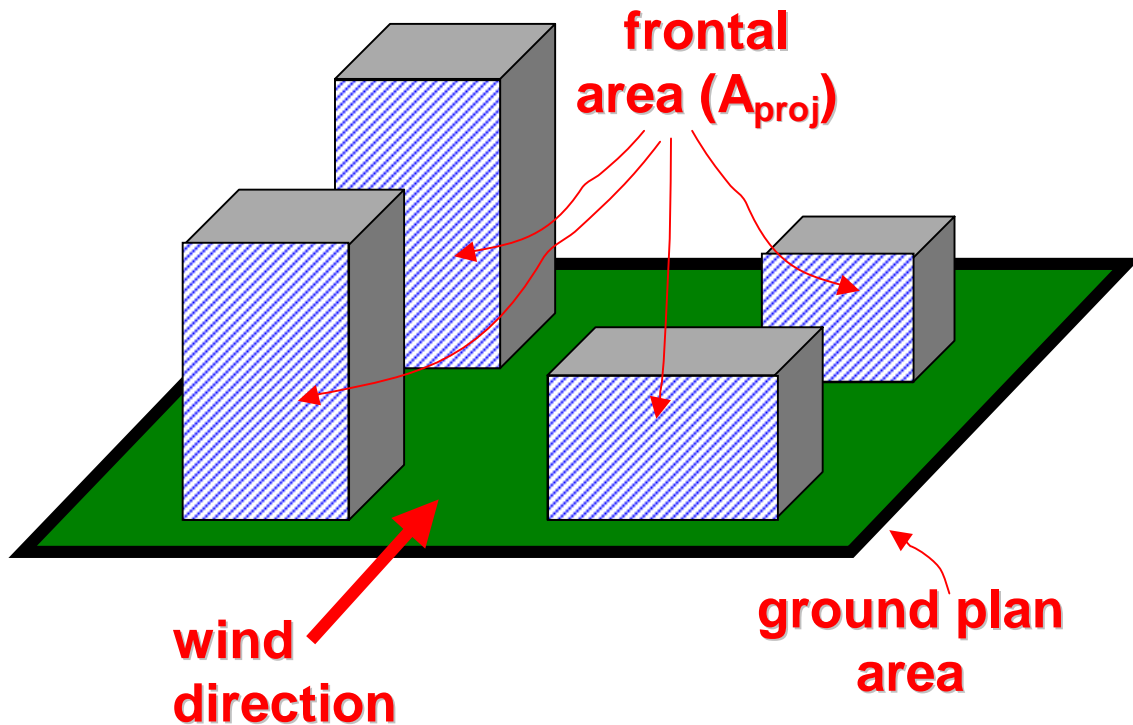
### 3.5 Building Frontal Area Index ( $\lambda_f$ )

Building walls facing into the wind impart drag on the air flow. The frontal area index, a measure of the frontal area per unit horizontal area, has been shown to be related to the surface roughness  $z_o$  (see Section 3.10). Surface roughness is used in air quality and meteorological models to account for enhanced mixing and the drag effects of the rough surface. The flow regime within urban street canyons is also thought to be a function of the frontal area index and plan area fraction (see Section 3.2).

The frontal area index ( $\lambda_f$ ) is defined as the total area of buildings projected into the plane normal to the approaching wind direction ( $A_{proj}$ ) divided by the plan area of the study site ( $A_T$ ):

$$\lambda_f(\theta) = \frac{A_{proj}}{A_T} \quad (12)$$

where  $\theta$  is the wind direction. Figure 30 illustrates frontal area. An Avenue script was written for use in the ArcView GIS to automatically determine the total area of building surfaces in the projected plane normal to a specified wind direction ( $A_{proj}$ ) and calculate  $\lambda_f$  using Eqn. (12).



**Figure 30.** Illustration of projected frontal area. In the schematic of the four buildings shown above, the frontal area ( $A_{proj}$ ) is the total area of the faces exposed to the oncoming wind.

The frontal area index ( $\lambda_f$ ) can be approximated from the product of mean height, breadth, and density of roughness elements (Grimmond and Oke 1999):

$$\lambda_f = \overline{L_y} \overline{H} \rho_d \quad (13)$$

where  $\overline{L_y}$  is the mean breadth of the roughness elements perpendicular to the wind direction,  $\overline{H}$  is the mean roughness element height, and  $\rho_d$  is the density (number) of roughness elements per unit area ( $\rho_d = n/A_T$ ).

Similar to the plan area fraction  $\lambda_p$ , the value of  $\lambda_f$  will be dependent on the location and the size of the area selected for analysis. Therefore, we have calculated  $\lambda_f$  for several different sized areas and as a function of land use. In addition, there is some ambiguity regarding the minimum distance between two adjacent buildings that should be used to distinguish the buildings as two separate buildings. The issue is that as two buildings are placed closer together the upstream building may start to mask the frontal face of the downstream building. For some applications, knowing the exposed frontal area may be more important than knowing the total frontal area. For example, for a cluster of buildings the drag may be better correlated to exposed frontal area as compared to total frontal area. For this study, we consider two separate buildings to be a single building only if the adjacent faces are touching. Using this rule we calculated the  $\lambda_f$  using the Avenue scripts for the entire 12-km<sup>2</sup> study area assuming the wind was approaching the city from the north, northeast, east, southeast, south, southwest, west, and northwest.

*Results.* Table 6 lists the computed  $\lambda_f$  values for the 12-km<sup>2</sup> study area for eight approach wind directions. For this large study area (i.e., an area with many buildings)  $\lambda_f$  is only slightly sensitive to approach flow wind direction. Because of the symmetrical characteristics of buildings it is expected that opposite wind directions (e.g., North and South) will have nearly identical frontal area indices. For our study area, the majority of streets run at about 45 degree angles to N-S and E-W. Hence, the along street directions are northeast, southeast, southwest, and northwest directions and have slightly smaller values.

**Table 6.** Summary of frontal area index ( $\lambda_f$ ) for downtown Los Angeles for several wind approach directions.

	North	Northeast	East	Southeast	South	Southwest	West	Northwest
$\lambda_f$	0.178	0.153	0.177	0.153	0.178	0.153	0.177	0.153

The value of  $\lambda_f$  is expected to be a function of land use because of the differences in building characteristics between different land uses. The relationship is also expected to be variable for samples of the same type of land use where building characteristics are highly variable, e.g., Urban High-rise, but not so variable for fairly homogeneous and consistent land uses, e.g.,

Single-family High-density Residential. Table 7 shows the  $\lambda_f$  values calculated for each land use type. Table 8 compares the computed  $\lambda_f$  for several land uses in Los Angeles to the computed  $\lambda_f$  for other cities and land uses. Note that we have not included trees in our calculation of the frontal area index, but several of the other studies cited in Table 8 have included trees.

Figure 31 shows the frontal area index for a north wind azimuth according to the non-uniform grid cell mesh. Calculations were not possible for the uniform 100-m X 100-m mesh because the grid cells are smaller than several buildings and buildings cross grid cell boundaries. This causes problems when trying to calculate the projected wall area in the grid cell. Some cells do not contain any walls because they are completely within the building. Rather than trying to develop a method to calculate  $\lambda_f$  for these instances we decided to forego the calculation of  $\lambda_f$  for the uniform grid cell mesh. Similar to the plan area fraction, we see smaller frontal area index values computed for areas including highway. Different from the plan area fraction distribution, we see the highest computed frontal area index values in the High-rise city center area, and lower values in the industrial regions. In general, the study area has a significant variation in computed frontal area index values. Several grid cells have computed values near zero, while several have computed values greater than 0.5. A direct relationship between land use and frontal area index is not demonstrated in this study area. Although we note the general trend of higher than average frontal area index values in the High-rise areas, this is not universal. For example, several grid cells contain tall buildings with small plan area fractions compared to the grid cell plan area, which results in a smaller than average frontal area index.

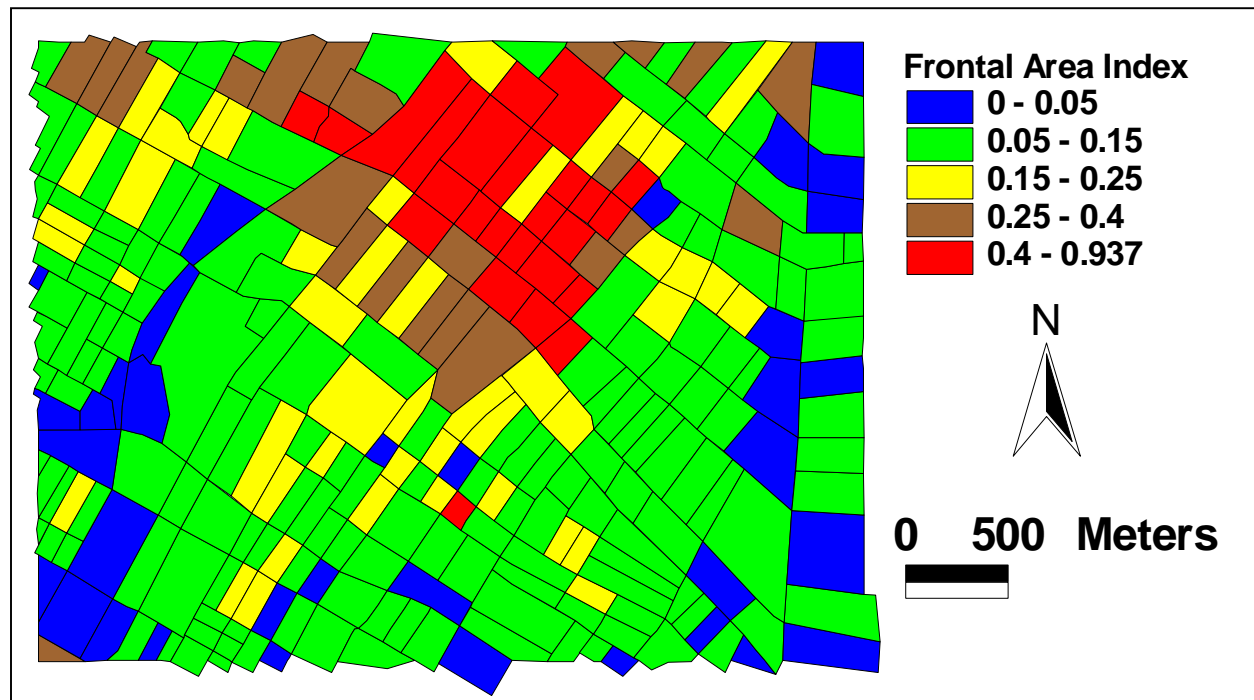
**Table 7.** Frontal area index ( $\lambda_f$ ) as a function of land use type.  
Four approach wind directions are included in the table.

Land Use Class	North	Northeast	East	Southeast
<b>Residential</b>	<b>0.190</b>	<b>0.168</b>	<b>0.183</b>	<b>0.166</b>
Low-density Single-family (< 8 units/hectare)	---	---	---	---
High-density Single-family ( $\geq 8$ units/hectare)	0.128	0.122	0.117	0.103
Multifamily	0.267	0.229	0.259	0.235
Mixed	0.127	0.118	0.122	0.111
<b>Commercial &amp; Services</b>	<b>0.266</b>	<b>0.227</b>	<b>0.265</b>	<b>0.225</b>
Non-high-rise	0.137	0.118	0.140	0.124
High-rise	0.553	0.470	0.542	0.448
<b>Industrial</b>	<b>0.100</b>	<b>0.087</b>	<b>0.101</b>	<b>0.092</b>
<b>Transportation/Communications/Utilities</b>	<b>0.012</b>	<b>0.012</b>	<b>0.011</b>	<b>0.010</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>0.140</b>	<b>0.115</b>	<b>0.142</b>	<b>0.120</b>
<b>Mixed Urban or Built-up</b>	<b>0.241</b>	<b>0.203</b>	<b>0.241</b>	<b>0.197</b>
<b>Other Urban or Built-up</b>	<b>0.035</b>	<b>0.029</b>	<b>0.028</b>	<b>0.031</b>
Predominantly Vegetated	0.019	0.019	0.018	0.018
Predominantly Built-up	0.070	0.050	0.048	0.058
<b>Urban High-rise</b>	<b>0.498</b>	<b>0.423</b>	<b>0.486</b>	<b>0.407</b>
<b>Downtown Core Area</b>	<b>0.419</b>	<b>0.350</b>	<b>0.417</b>	<b>0.345</b>

**Table 8.** Comparison of frontal area index ( $\lambda_f$ ) for several cities and land uses

Location	Land Use Class	$\lambda_f$	Source
Arcadia, CA	Suburban residential	0.33	Grimmond and Oke (1999)
Chicago, IL	Suburban residential	0.28	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Multifamily residential</b>	<b>0.25</b>	<b>This report*</b>
Sacramento, CA	Suburban residential	0.23	Grimmond and Oke (1999)
Chicago, IL	Suburban residential	0.21	Grimmond and Oke (1999)
Tucson, AZ	Suburban residential	0.19	Grimmond and Oke (1999)
Vancouver, BC, Canada	Suburban residential	0.19	Grimmond and Oke (1999)
Miami, FL	Suburban residential	0.16	Grimmond and Oke (1999)
San Gabriel, CA	Suburban residential	0.14	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>High-density single-family residential</b>	<b>0.12</b>	<b>This report*</b>
Vancouver, BC, Canada	Light Industrial	0.13	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Industrial</b>	<b>0.10</b>	<b>This report*</b>
<b>Los Angeles, CA</b>	<b>Urban high-rise</b>	<b>0.45</b>	<b>This report*</b>
<b>Los Angeles, CA</b>	<b>Downtown core area</b>	<b>0.38</b>	<b>This report*</b>
Vancouver, BC, Canada	Central city	0.30	Grimmond and Oke (1999)
Mexico City, Mexico	Central city	0.19	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Non-high-rise commercial &amp; services</b>	<b>0.13</b>	<b>This report*</b>

\*The values shown from this study are the average values for eight wind directions (north, northeast, east, southeast, south, southwest, west, northwest).

**Figure 31.** Spatial distribution of building frontal area index ( $\lambda_f$ ) for a north wind azimuth.

### 3.6 Frontal Area Density ( $a_f(z)$ )

The frontal area is often used in computing the drag force on solid objects immersed in fluids. The frontal area density, a measure of the frontal area per unit horizontal area per unit height increment, has been used by researchers in the plant canopy and urban canopy communities to help quantify the drag force as a function of height. The drag force approach allows one to compute the area-averaged wind profile within the canopy.

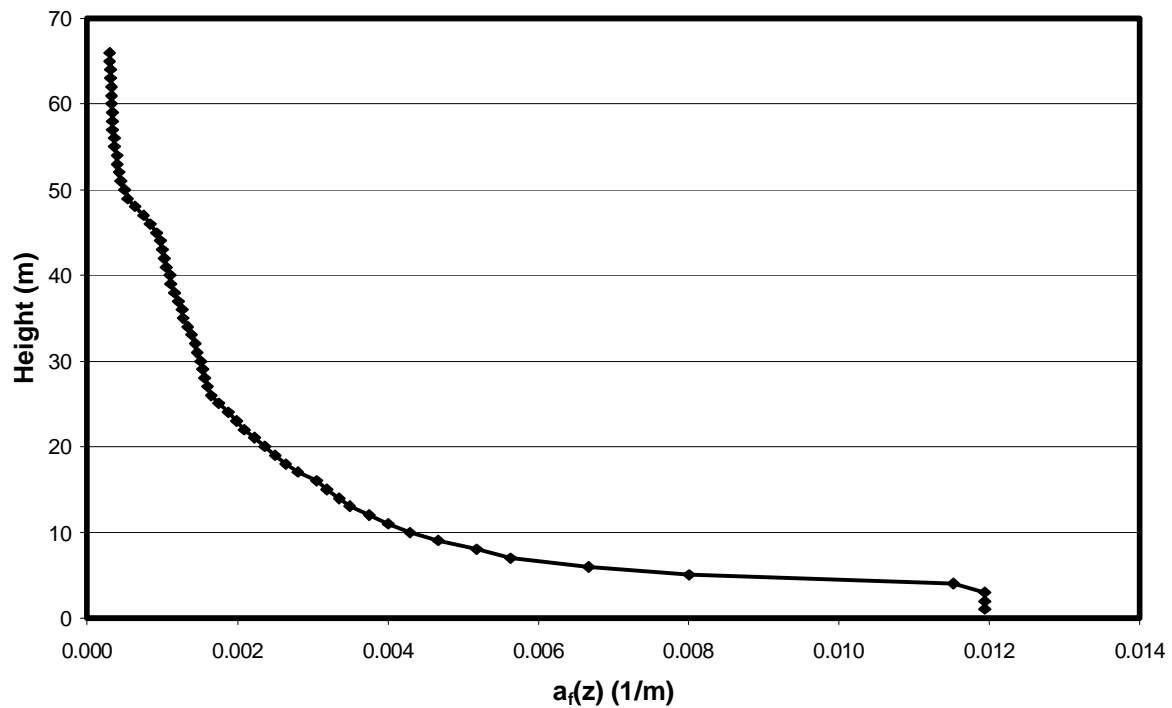
The frontal area density ( $a_f(z)$ ) is defined as:

$$a_f(z, \theta) = \frac{A(\theta)_{proj(\Delta z)}}{A_T \Delta z} \quad (14)$$

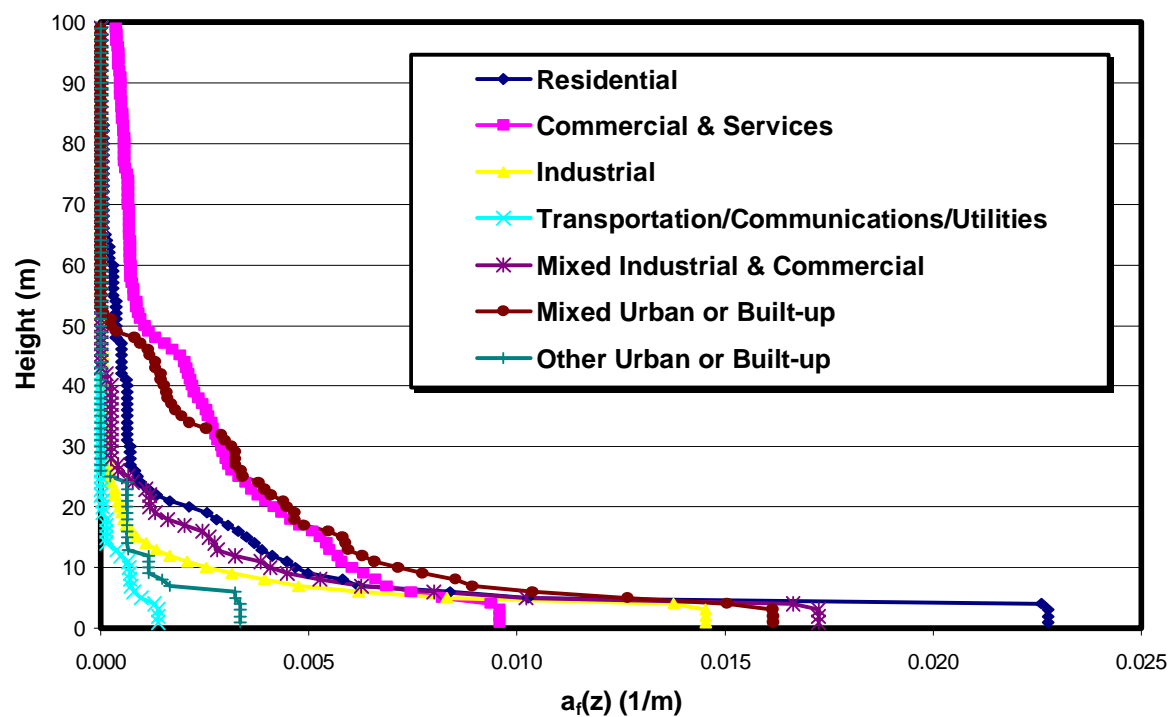
where  $A(\theta)_{proj(\Delta z)}$  is the area of building surfaces projected into the plane normal to the approaching wind direction for a specified height increment ( $\Delta z$ ),  $\theta$  is the wind direction angle, and  $A_T$  is the total plan area of the study site. For a specified wind direction, the integral of  $a_f(z)$  over the canopy height equates to  $\lambda_f$ .

*Results.* We performed the frontal area density calculations at one-meter increments. Figure 32 shows  $a_f(z)$  for the Los Angeles study area for a wind approaching from the north. Figure 33 shows the  $a_f(z)$  functions for the land use types in the 7-category scheme that have a sufficient number of buildings and land area to produce meaningful results. Figure 34 shows the  $a_f(z)$  functions for the 13-category land use scheme and the Urban High-rise and Downtown Core Area land uses.

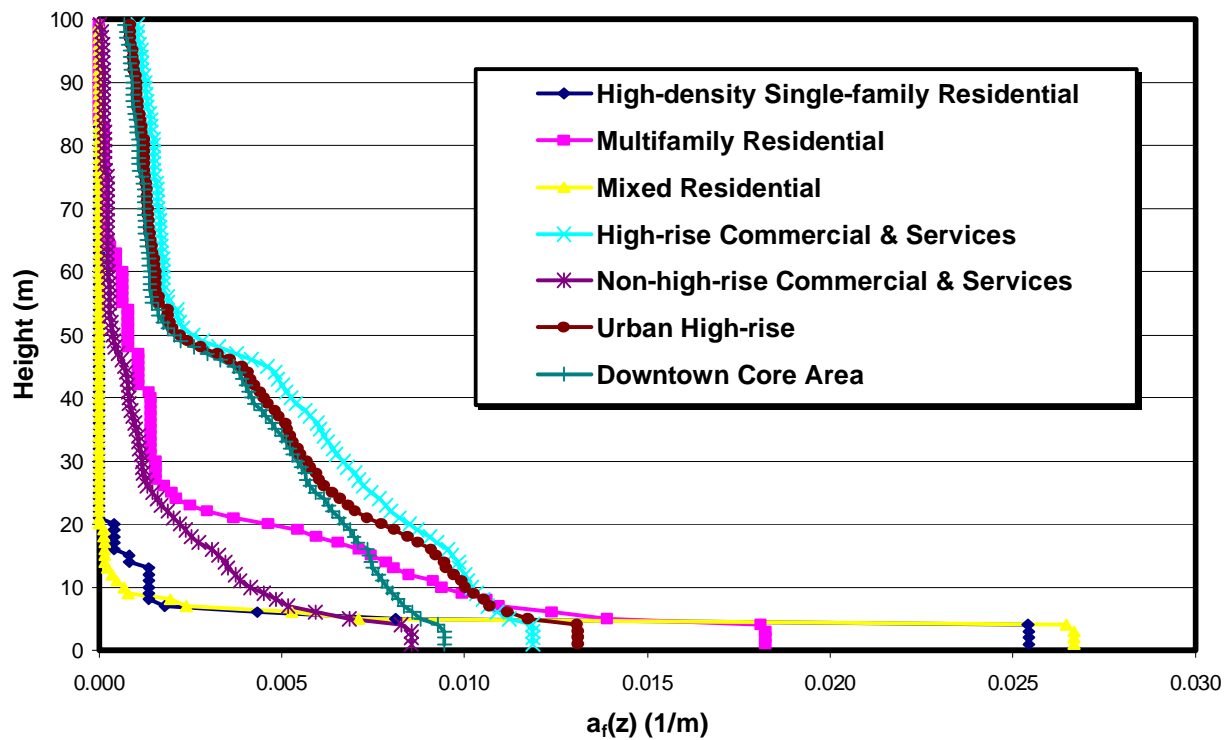
Interestingly, the frontal area density near the ground is largest for Residential areas. This occurs due to the preponderance of shorter buildings in Residential areas (many short buildings occupying the same volume as a few taller buildings have more frontal area). Industrial land use has relatively high frontal area density near the ground as well, greater than Commercial & Services and Urban High-rise. Presumably Commercial & Services Non-high-rise has a relatively low frontal area density near the surface due to wide, squat buildings, like shopping centers and strip malls with large open parking lots. The frontal area density decays most rapidly with height for Residential and Industrial areas due to low building heights. The Urban High-rise land use decays most slowly with height due to the large number of tall buildings in this land use type.



**Figure 32.** Frontal area density function ( $a_f(z)$ ) for the Los Angeles study area for a wind approaching from the north.



**Figure 33.** Frontal area density function ( $a_f(z)$ ) for land use types in the 7-category scheme for a wind approaching from the north.



**Figure 34.** Frontal area density function ( $a_f(z)$ ) for several land use types in the 13-category scheme and the Urban High-rise and Downtown Core Area land uses for a wind approaching from the north.

### 3.7 Complete Aspect Ratio ( $\lambda_C$ )

The “complete” surface area, including building walls, roofs, and ground surfaces, is important when evaluating the urban canopy energy budget in a city. All of these surfaces act as sources and sinks of heat and need to be accounted for when evaluating the energy balance of an urbanized area. The non-dimensional form of the complete surface area, the complete aspect ratio, is useful in interpreting surface temperatures derived from remote sensing instruments. Used with the plan area  $\lambda_p$ , some notion of the three-dimensionality of the urban fabric can be obtained and better estimates of the “real” skin temperature might be computed.

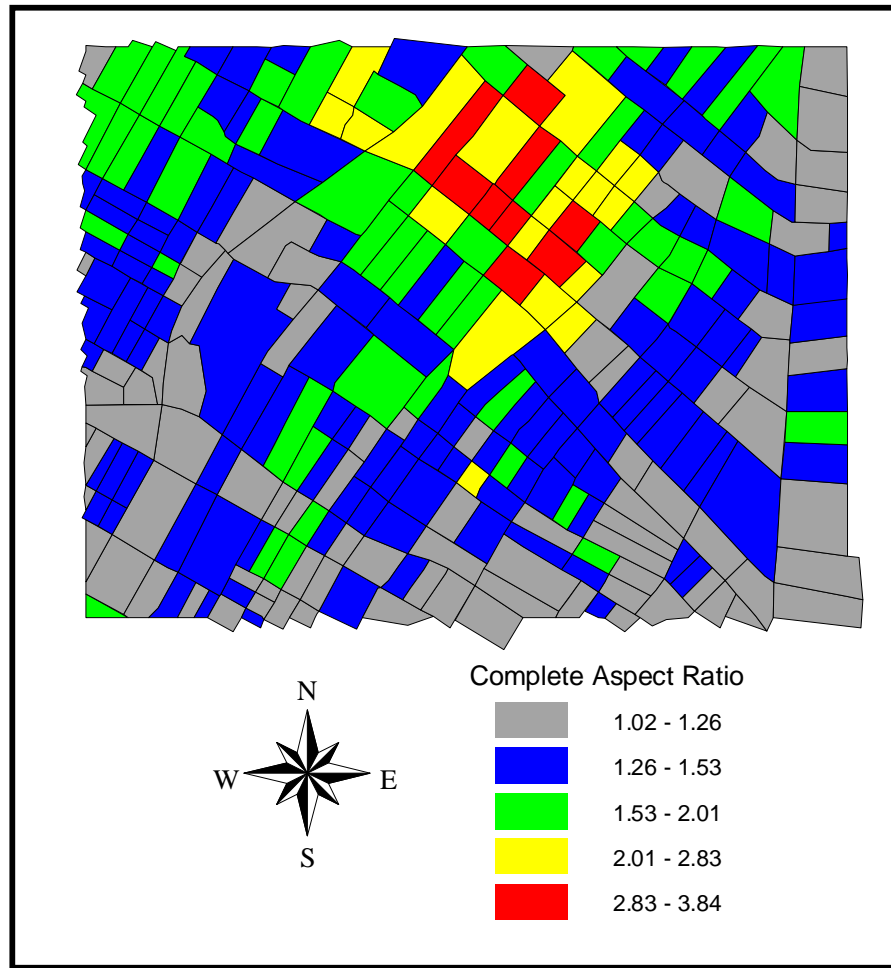
The complete aspect ratio ( $\lambda_C$ ) is defined as the summed surface area of roughness elements and exposed ground divided by the total plan area (Voogt and Oke 1997):

$$\lambda_C = \frac{A_C}{A_T} = \frac{A_W + A_R + A_G}{A_T} \quad (15)$$

where  $A_C$  is the combined surface area of the buildings and exposed ground,  $A_W$  is the wall surface area,  $A_R$  is the roof area,  $A_G$  is the area of exposed ground, and  $A_T$  is the plan area of the study site.  $A_C$  is calculated by summing the surface area of the buildings and the difference between the total plan area of the site and the plan area of buildings at ground level (i.e., the exposed ground surface). For dense urban areas with flat roofed buildings and without much vegetation,  $A_C$  can be approximated as the sum of the plan area of the site and the area of building walls (not including rooftops).

Using an Avenue script in the ArcView GIS we automatically calculated  $\lambda_C$  for the entire city for a non-uniform grid cell mesh (shown in Figure 22) and as a function of land use. Calculations were not possible for the uniform 100-m X 100-m mesh for the same reasons described for frontal area index. The rooftop surface area was calculated assuming the rooftops were flat, which a digital orthophoto indicated to be true for most of the land use types, except for some of the High-density Single-family Residential areas. Another source of error in our complete aspect ratio calculation is the neglect of the surface area of trees and bushes. Grimmond and Oke (1999) found the surface area of trees and bushes to be an important component of the complete surface area, especially in residential areas. However, the presence of trees and bushes is minimal in the particular downtown area of Los Angeles selected for analysis.

*Results.* For the 12-km<sup>2</sup> study area, the  $\lambda_C$  was calculated to be 1.51. The  $\lambda_C$  for each grid cell was calculated for the non-uniform grid cell mesh (Figure 35). For the non-uniform mesh, the mean  $\lambda_C$  was 1.50, with a standard deviation of 0.48, and a range of 1.02 to 3.84. The high-rise area is located in the area of red grid cells in Figure 35. The computed  $\lambda_C$  values for each land use type in our classification schemes are shown in Table 9. The  $\lambda_C$  values for the downtown area are in the range of 1.53 to 3.84, which are consistent with the central city values from other studies shown in Table 10.



**Figure 35.** Display of complete aspect ratio ( $\lambda_c$ ) calculated for the Los Angeles downtown area per grid cell.

**Table 9.** Complete aspect ratio ( $\lambda_c$ ) for each land use type

Land Use Class	$\lambda_c$
<b>Residential</b>	<b>1.55</b>
Low-density Single-family (< 8 units/hectare)	---
High-density Single-family ( $\geq 8$ units/hectare)	1.36
Multifamily	1.77
Mixed	1.37
<b>Commercial &amp; Services</b>	<b>1.78</b>
Non-high-rise	1.41
High-rise	2.60
<b>Industrial</b>	<b>1.30</b>
<b>Transportation/Communications/Utilities</b>	<b>1.04</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>1.41</b>
<b>Mixed Urban or Built-up</b>	<b>1.69</b>
<b>Other Urban or Built-up</b>	<b>1.10</b>
Predominantly Vegetated	1.06
Predominantly Built-up	1.18
<b>Urban High-rise</b>	<b>2.44</b>
<b>Downtown Core Area</b>	<b>2.22</b>

Table 10 compares selected values from Table 9 with  $\lambda_c$  values computed for other cities. The  $\lambda_c$  computed for Los Angeles Residential land use is within the range of values found for other cities. The  $\lambda_c$  computed for the Industrial land use type in the Los Angeles study area is similar to the value computed for a light industrial area in Vancouver. The downtown high-rise land use types in Los Angeles have higher  $\lambda_c$  values compared to values computed for Vancouver, Mexico City, and Singapore.

**Table 10.** Complete aspect ratio ( $\lambda_c$ ) for downtown Los Angeles and other cities

Location	Land Use Class	$\lambda_c$	Source
Arcadia, CA	Suburban residential	1.78	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Multifamily residential</b>	<b>1.77</b>	<b>This report</b>
Chicago, IL	Suburban residential	1.74	Grimmond and Oke (1999)
Vancouver, BC, Canada	Suburban residential	1.65	Voogt and Oke (1997)
Sacramento, CA	Suburban residential	1.63	Grimmond and Oke (1999)
Chicago, IL	Suburban residential	1.51	Grimmond and Oke (1999)
Tucson, AZ	Suburban residential	1.45	Grimmond and Oke (1999)
Miami, FL	Suburban residential	1.37	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>High-density single-family residential</b>	<b>1.36</b>	<b>This report</b>
San Gabriel, CA	Suburban residential	1.31	Grimmond and Oke (1999)
Vancouver, BC, Canada	Light industrial	1.39	Voogt and Oke (1997)
<b>Los Angeles, CA</b>	<b>Industrial</b>	<b>1.30</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>High-rise commercial &amp; services</b>	<b>2.60</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>Urban high-rise</b>	<b>2.44</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>Downtown core area</b>	<b>2.22</b>	<b>This report</b>
Vancouver, BC, Canada	Central city	2.20	Voogt and Oke (1997)
Mexico City, Mexico	Central city	1.73	Grimmond and Oke (1999)
Singapore	Downtown	1.70	Nichol (1996)

### 3.8 Building Surface Area to Plan Area Ratio ( $\lambda_B$ )

Another measure of urban terrain character is the ratio of built surface area to the plan surface area. Like the complete aspect ratio (Section 3.7), the building surface area is important when evaluating the urban canopy energy budget in a city. Building walls and roof surfaces act as sources and sinks of heat and need to be accounted for when evaluating the energy balance of an urbanized area. Perhaps some combination of frontal area, plan area, complete surface area, and building surface area parameters will allow for better parameterizations of the urban canopy energy budget.

The building surface area to plan area ratio ( $\lambda_B$ ) is defined as the sum of building surface area divided by the total plan area:

$$\lambda_B = \frac{A_R + A_W}{A_T} \quad (16)$$

where  $A_R$  is the plan area of rooftops,  $A_W$  is the total area of non-horizontal roughness element surfaces (e.g., walls), and  $A_T$  is the total plan area of the study location. For the calculations below, we have made a flat-roof assumption.

*Results.* The  $\lambda_B$  for the 12-km<sup>2</sup> study location in Los Angeles was calculated to be 0.82. Table 11 shows the computed  $\lambda_B$  values for each land use type included in the building analysis. Commercial & Services High-rise, Urban High-rise, and Downtown Core Area have the largest values due to the presence of tall buildings and fairly high plan area fraction. We did not find values for other cities for this parameter.

**Table 11.** Building surface area to plan area ratio ( $\lambda_B$ ) for each land use type

Land Use Class	$\lambda_B$
<b>Residential</b>	<b>0.85</b>
Low-density Single-family (< 8 units/hectare)	---
High-density Single-family ( $\geq 8$ units/hectare)	0.63
Multifamily	1.08
Mixed	0.66
<b>Commercial &amp; Services</b>	<b>1.06</b>
Non-high-rise	0.67
High-rise	1.92
<b>Industrial</b>	<b>0.68</b>
<b>Transportation/Communications/Utilities</b>	<b>0.07</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>0.87</b>
<b>Mixed Urban or Built-up</b>	<b>1.03</b>
<b>Other Urban or Built-up</b>	<b>0.17</b>
Predominantly Vegetated	0.10
Predominantly Built-up	0.32
<b>Urban High-rise</b>	<b>1.75</b>
<b>Downtown Core Area</b>	<b>1.50</b>

### 3.9 Height-to-Width Ratio ( $\lambda_s$ )

The ratio of the height of buildings to the horizontal distance (or street width) between the buildings is called the height-to-width ratio ( $\lambda_s$ ). The height-to-width ratio has been found, for idealized arrangements of same-height buildings, to determine the flow regime. Hussain and Lee (1980) performed wind-tunnel experiments and found the three flow regimes develop in idealized urban street canyons: (1) isolated flow, (2) wake interference flow, and (3) skimming flow. The isolated flow regime occurs when elements are spaced relatively far apart ( $\lambda_s < 0.4$ ), the wake interference flow occurs when elements are spaced at a medium density level ( $0.4 < \lambda_s < 0.7$ ), and the skimming flow regime occurs for high-density building arrangements ( $\lambda_s > 0.7$ ) (Oke 1988).

The height-to-width ratio ( $\lambda_s$ ) (also called the street aspect ratio) is calculated for two buildings by dividing the average height by the distance between the two buildings:

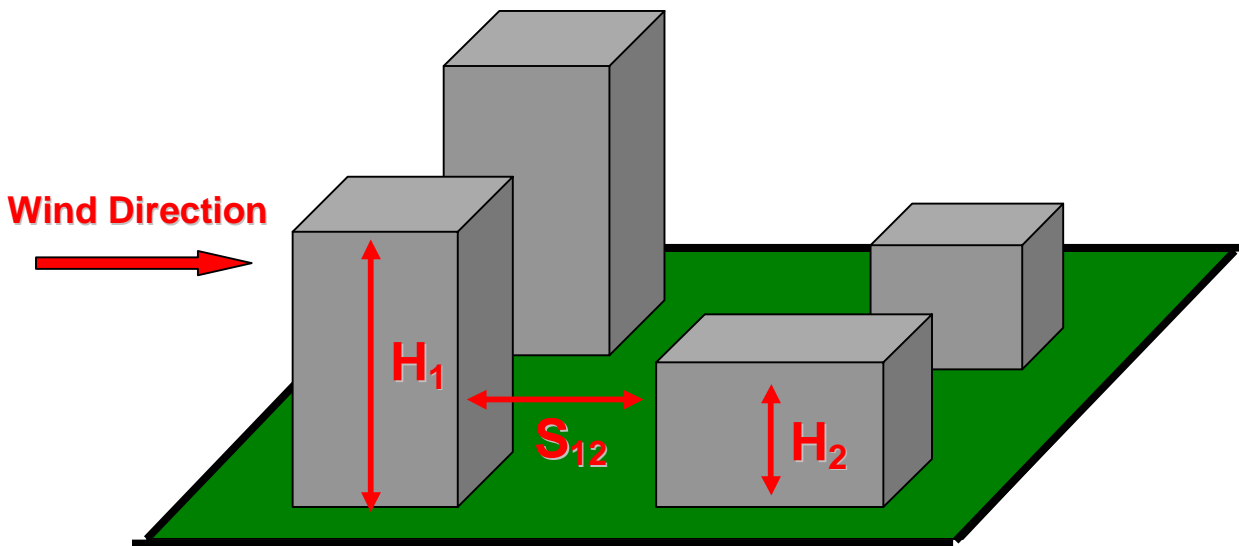
$$\lambda_s = \frac{(H_1 + H_2)/2}{S_{12}} \quad (17)$$

where  $H_1$  is the height of the upwind building,  $H_2$  is the height of the downwind building, and  $S_{12}$  is the horizontal distance between the two buildings (i.e., the canyon width). Figure 36 illustrates the measures used to compute  $\lambda_s$ . The calculation of  $\lambda_s$  is performed for each pair of adjacent elements in a building array, which can be very tedious for the complex building shapes and patterns in a city. For idealized arrangements of buildings, the calculation of an average  $\lambda_s$  can be approximated by taking the average building height divided by the average width between buildings (Grimmond and Oke 1999):

$$\overline{\lambda_s} \cong \frac{\overline{z_H}}{\overline{W}} \quad (18)$$

where  $\overline{z_H}$  is the average building height and  $\overline{W}$  is the average distance between buildings.

Due to the large number of buildings in the Los Angeles dataset, an automated approach is warranted. Because of the complexity of the Los Angeles downtown area, we did not use the simplified methodology described by Eqn. (18). Instead, we computed  $\lambda_s$  along linear traverses across the city at different angles using Eqn. (17). Our calculation strategy involved converting the urban building database into a raster digital elevation model (DEM – a matrix of numbers representing building height). Then traversing along each row or column of grid cells the height-to-width ratio was calculated between each pair of buildings. A Fortran code was written to execute this procedure. Since this approach yields  $\lambda_s$  values in non-preferred directions (e.g., running along a street, not across a street), we then superimposed the matrices of traverses done at different angles, and chose the height-to-width ratio at each grid cell by selecting the largest value.

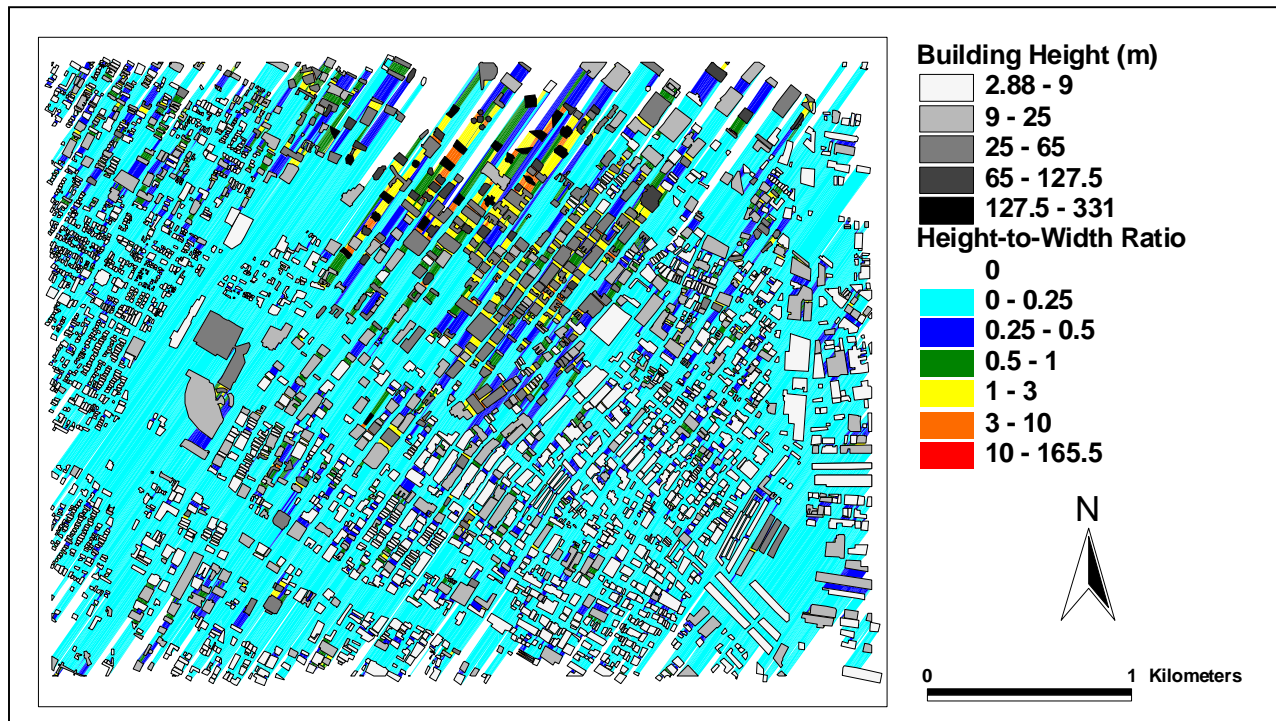


**Figure 36.** Illustration of the height-to-width ratio parameters.

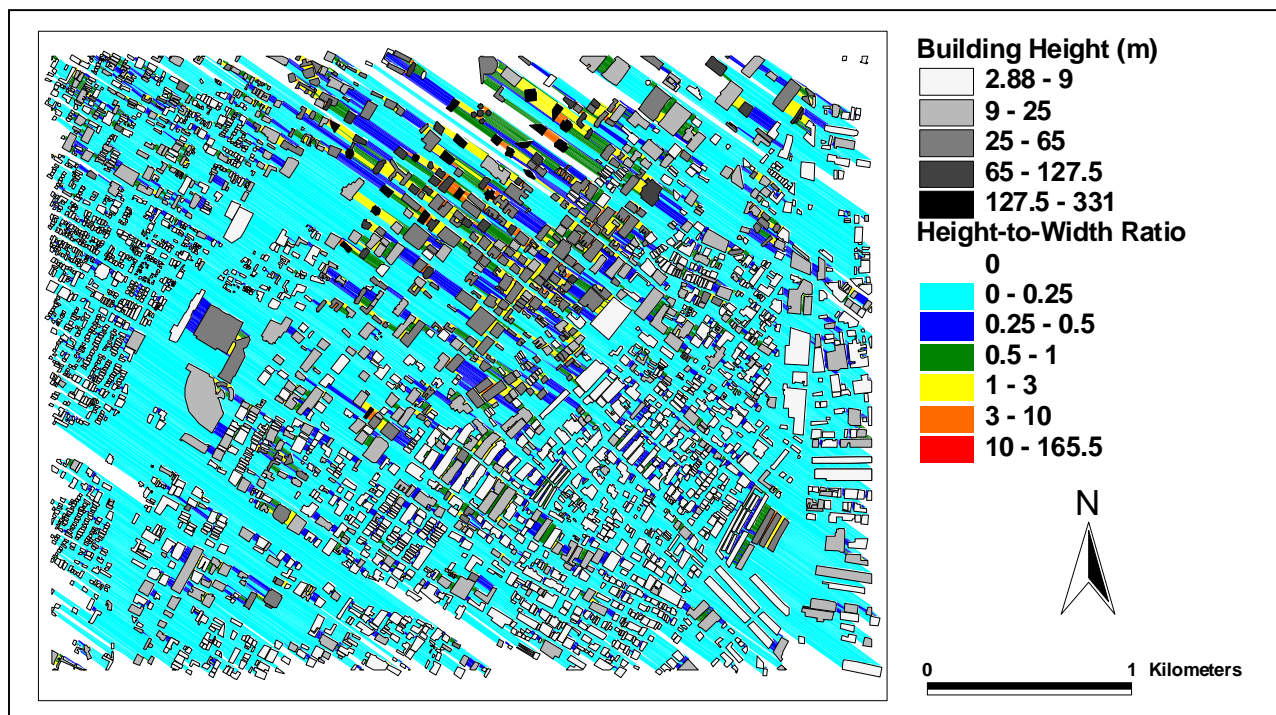
Figures 37 and 38 show the spatial distribution of the computed  $\lambda_s$  values for the two analysis directions that corresponded with the predominant street directions. Due to the unidirectional nature of the traverses, one can plainly see that the height-to-width ratio is too small between some buildings. For example, in Fig. 36 the  $\lambda_s$  values are underestimated along the southwesterly-to-northeasterly-running streets. Figure 39 shows the composite  $\lambda_s$  values, which were computed at each grid cell by selecting the largest value from the superimposed matrices from the two traversal directions, i.e., superimposing the values from Figs. 37 and 38. The higher  $\lambda_s$  values are clearly visible in the downtown area of Los Angeles (the buildings are colored by height).

Figures 40, 41, and 42 show the composite  $\lambda_s$  values for areas predominantly composed of Residential, Industrial, and Urban High-rise land uses, respectively. The figures clearly illustrate the concentration of the highest  $\lambda_s$  values in the High-rise area. The  $\lambda_s$  values are fairly similar for the Residential and Industrial land uses.

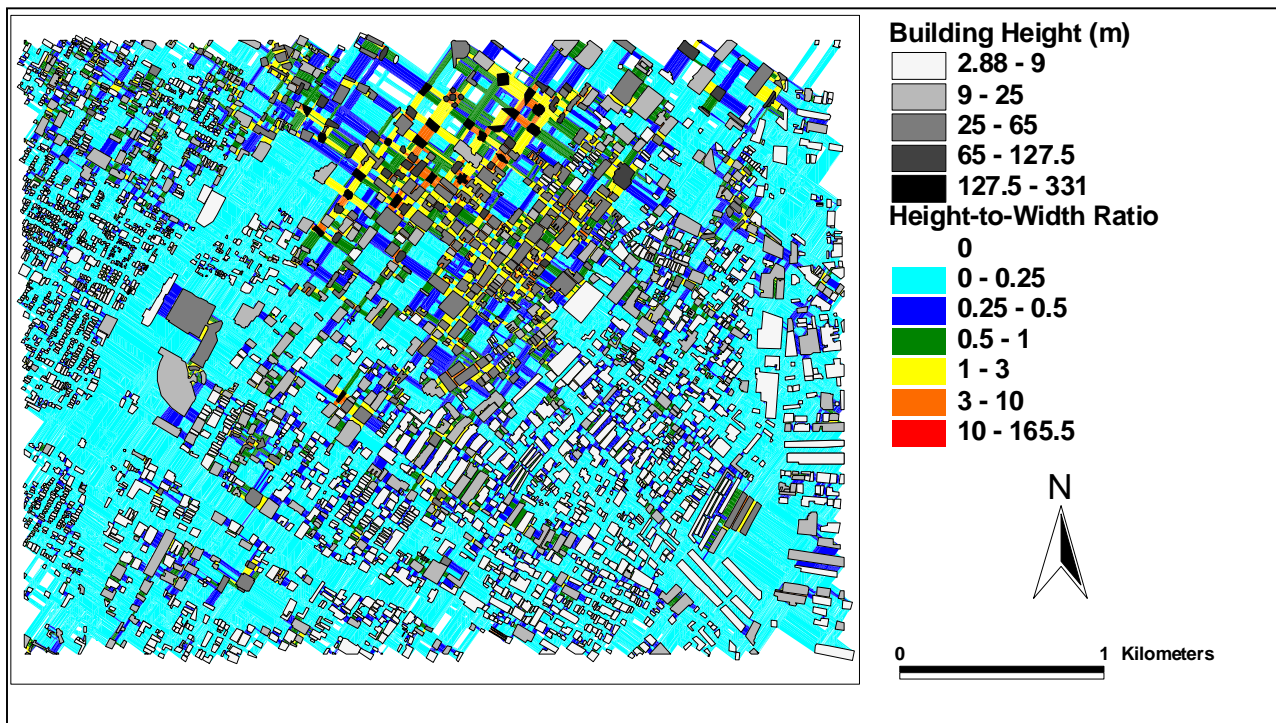
We also computed the average  $\lambda_s$  values for the study area and for each land use type in our classification schemes. The average  $\lambda_s$  was computed by using the area-weighted average of the spatial distribution of the composite height-to-width ratio shown in Figure 39. One could also weight the average  $\lambda_s$  by number of buildings, streets, or some other quantity. In the approach used here, buildings with larger footprints will exert a greater influence over the area-weighted average. In addition, open areas (e.g., parking lots and parks) and street intersections will be counted in the average.



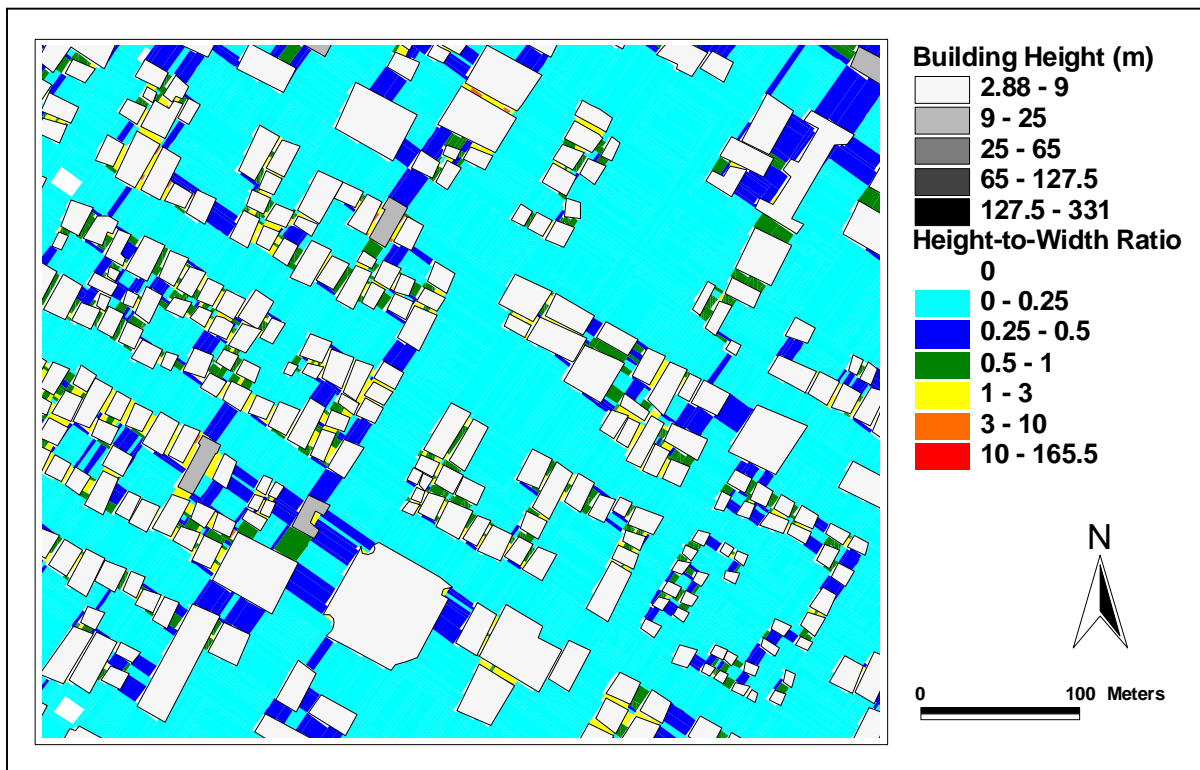
**Figure 37.** Computed “single-direction” height-to-width ratio ( $\lambda_s$ ) for the Los Angeles study area (analysis traversal was from the northeast to southwest).



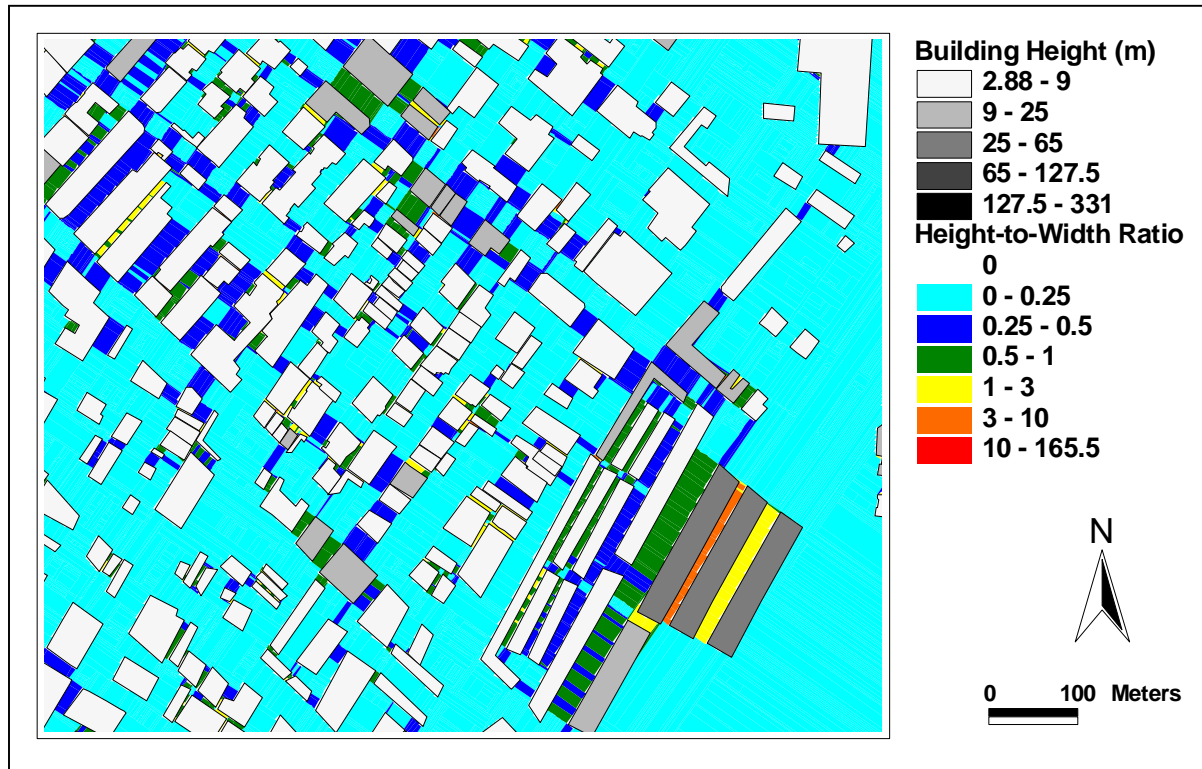
**Figure 38.** Computed “single-direction” height-to-width ratio ( $\lambda_s$ ) for the Los Angeles study area (analysis traversal was from the northwest to the southeast).



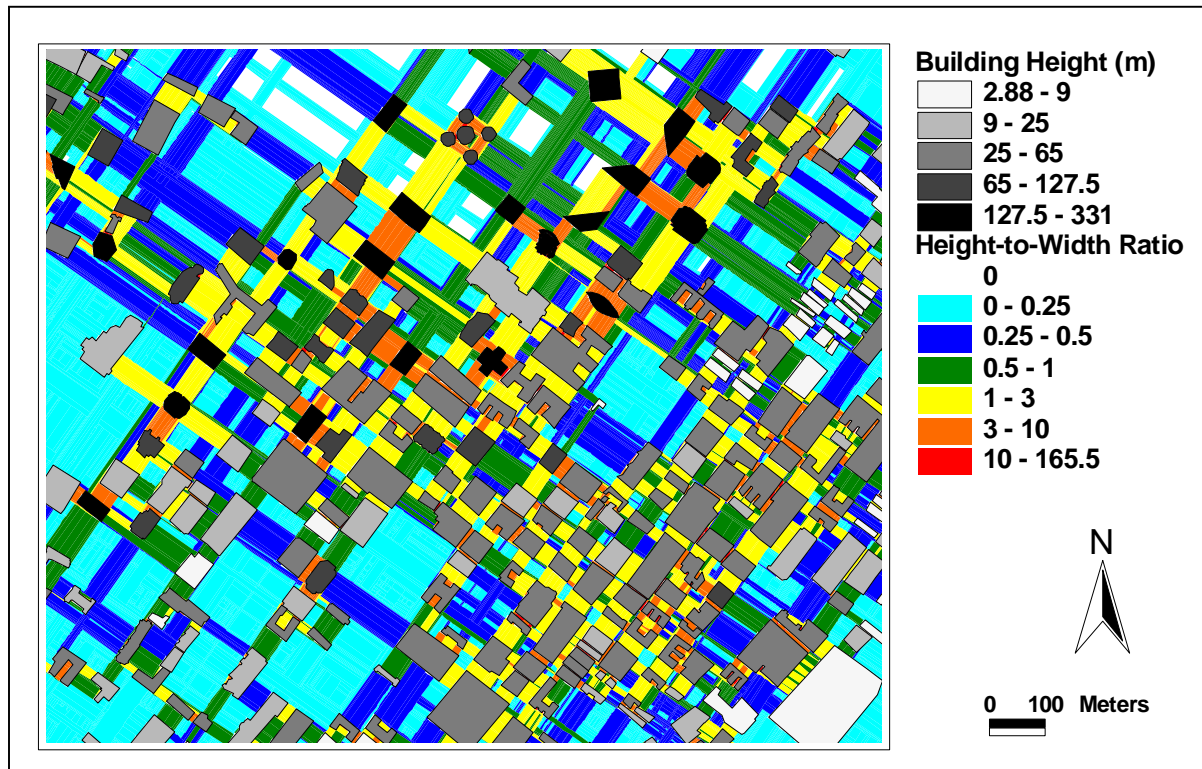
**Figure 39.** Composite height-to-width ratio ( $\lambda_s$ ) for the Los Angeles study area based on the integration of computed values for the two analysis traversals.



**Figure 40.** Composite height-to-width ratio ( $\lambda_s$ ) for a Residential section of the Los Angeles study area.



**Figure 41.** Composite height-to-width ratio ( $\lambda_s$ ) for an Industrial section of the Los Angeles study area.



**Figure 42.** Composite height-to-width ratio ( $\lambda_s$ ) for the Urban High-rise section of the Los Angeles study area.

*Results.* The area-weighted average  $\lambda_s$  for the study area was calculated to be 0.33. The range of  $\lambda_s$  for the study area was 0 to 165.5. Zero values occur where buildings are located and in regions where two buildings do not lie on an ‘along-the-street’ or ‘across-the-street’ transect. Table 12 lists the area-weighted average  $\lambda_s$  values for each land use type.

**Table 12.** Area-weighted average composite height-to-width ratio ( $\lambda_s$ )

Land Use Class	$\lambda_s$
<b>Residential</b>	<b>0.33</b>
Low-density Single-family (< 8 units/hectare)	---
High-density Single-family ( $\geq 8$ units/hectare)	0.23
Multifamily	0.45
Mixed	0.24
<b>Commercial &amp; Services</b>	<b>0.47</b>
Non-high-rise	0.28
High-rise	0.91
<b>Industrial</b>	<b>0.20</b>
<b>Transportation/Communications/Utilities</b>	<b>0.08</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>0.34</b>
<b>Mixed Urban or Built-up</b>	<b>0.43</b>
<b>Other Urban or Built-up</b>	<b>0.16</b>
Predominantly Vegetated	0.13
Predominantly Built-up	0.08
<b>Urban High-rise</b>	<b>0.82</b>
<b>Downtown Core Area</b>	<b>0.77</b>

Table 13 compares selected values from our study with values computed for other cities. The values we calculated for Los Angeles are on the lower end of the range of values from other cities. The much larger values computed in other studies for the Residential land use are most likely attributable to the inclusion of trees in the height-to-width calculations. In addition, the presence of two major highways in our study area makes the average building density smaller, which has the effect of reducing the overall composite height-to-width ratios in some areas. Also, the northern end of the downtown area we studied included an area with significant grassed open space and parking lots, which reduced the composite height-to-width ratios for that area. Finally, the averaging scheme could cause significant differences; sensitivity studies need to be performed.

**Table 13.** Comparison of height-to-width ( $\lambda_s$ ) for downtown Los Angeles and other cities

Location	Land Use Class	$\lambda_s$	Source
Sacramento, CA	Suburban residential	1.21	Grimmond and Oke (1999)
Arcadia, CA	Suburban residential	1.19	Grimmond and Oke (1999)
Miami, FL	Suburban residential	1.03	Grimmond and Oke (1999)
Chicago, IL	Suburban residential	0.97	Grimmond and Oke (1999)
Vancouver, BC, Canada	Suburban residential	0.90	Grimmond and Oke (1999)
Tucson, AZ	Suburban residential	0.54	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Multifamily residential</b>	<b>0.45</b>	<b>This report</b>
San Gabriel, CA	Suburban residential	0.43	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>High-density Single-family residential</b>	<b>0.23</b>	<b>This report</b>
Vancouver, BC, Canada	Light industrial	0.57	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Industrial</b>	<b>0.20</b>	<b>This report</b>
Vancouver, BC, Canada	Central city	1.40	Grimmond and Oke (1999)
Mexico City, Mexico	Central city	1.19	Grimmond and Oke (1999)
<b>Los Angeles, CA</b>	<b>Commercial &amp; services high-rise</b>	<b>0.91</b>	<b>This report</b>
<b>Los Angeles, CA</b>	<b>Downtown core area</b>	<b>0.77</b>	<b>This report</b>

### 3.10 Aerodynamic Roughness Parameters

The representation of surface roughness is a critical first step in many meteorological, wind engineering, and pollutant dispersion modeling activities. It provides an estimate of the drag and turbulent mixing associated with the underlying surface. The displacement height ( $z_d$ ) and roughness length ( $z_o$ ) are key parameters in the logarithmic velocity profile based on similarity theory and is commonly used in many models to specify the boundary conditions above built-up areas. The displacement height can be conceptualized as the height of a surface formed by distributing the aggregate volume of roughness elements and their wake re-circulation cavities uniformly over the underlying surface (Macdonald et al. 1998). The roughness length is directly related to the overall drag of the surface. Mathematically, it represents the distance above the displacement height plane at which the velocity goes to zero.

Both  $z_d$  and  $z_o$  are difficult to estimate with certainty by experiment or theory. Grimmond and Oke (1999) reviewed methods to calculate the  $z_d$  and  $z_o$  of urban areas based on building and vegetation morphology. They compared the predictions of the morphological methods to those obtained from wind measurements in urban areas. Using the equations rated amongst the most appropriate by Grimmond and Oke (1999), we calculated values of  $z_d$  and  $z_o$  for the entire Los Angeles study area, spatially over a defined grid and as a function of land use in the study area. Note that the similarity theory is not valid in horizontally inhomogeneous areas and that for many urban areas the roughness parameter concept will not hold or can only be applied well above the roughness elements.

The most common method used to calculate the displacement height ( $z_d$ ) and roughness length ( $z_o$ ) are simple rules-of-thumb (Grimmond and Oke 1999):

$$z_d = f_d \overline{z_H} \quad (19)$$

and

$$z_o = f_o \overline{z_H} \quad (20)$$

where  $\overline{z_H}$  is the average building height and  $f_d$  and  $f_o$  are empirical coefficients. Approximations for urban values are 0.5 for  $f_d$  and 0.1 for  $f_o$ . Beyond the limitations of applying these equations to horizontally inhomogeneous urban areas, these equations also only hold for medium building density situations, as it is known that  $z_o$  and  $z_d$  vary with building spacing.

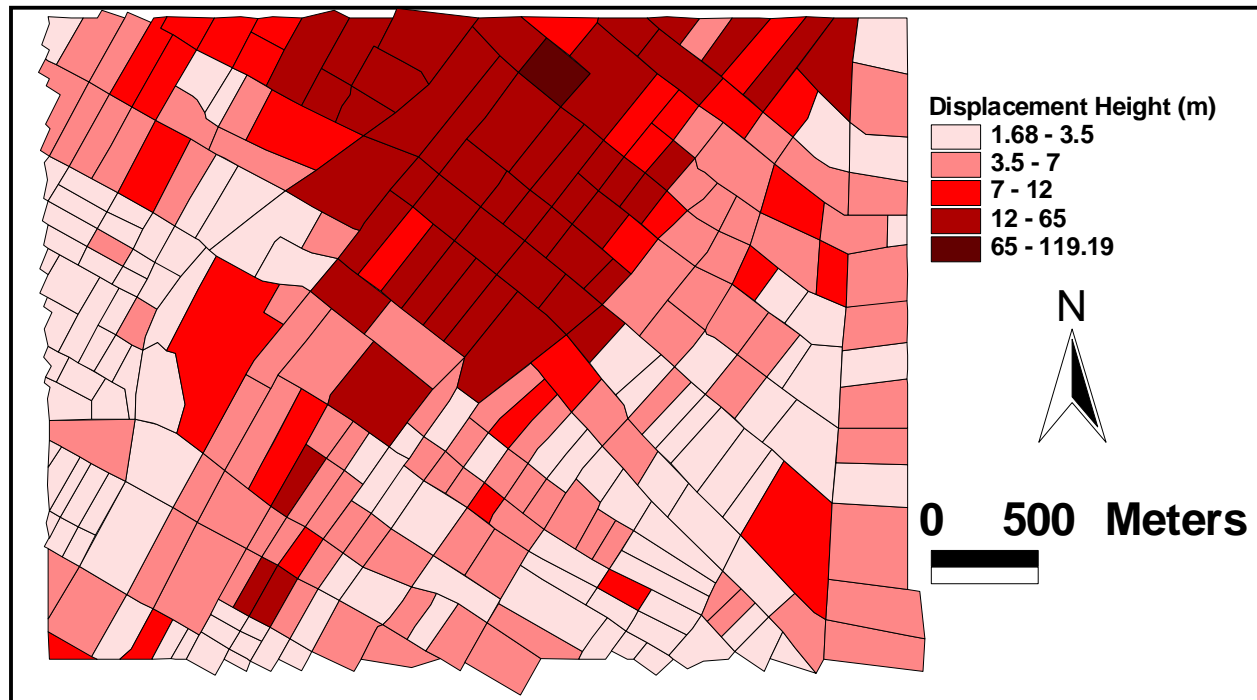
*Results.* Although Eqns. (19) and (20) may not hold for all areas in our study domain, we have still computed the aerodynamic roughness parameters for the Los Angeles study area for comparison purposes. Using these approximations we found that  $z_d \approx 5.98$  m and  $z_o \approx 1.20$  m when using the mean building height, and  $z_d \approx 8.50$  m and  $z_o \approx 1.70$  m when using the plan-area-weighted average building height. Table 14 lists the computed  $z_d$  and  $z_o$  values for each land use type using the mean building height and Eqns. (19) and (20). Table 15 lists the computed  $z_d$  and  $z_o$  values for each land use type using the plan-area-weighted average building height and Eqns. (19) and (20), while Figures 43 and 44 show the spatial distribution of the  $z_d$  and  $z_o$ .

**Table 14.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ): simple rules-of-thumb eqns. and average building height.

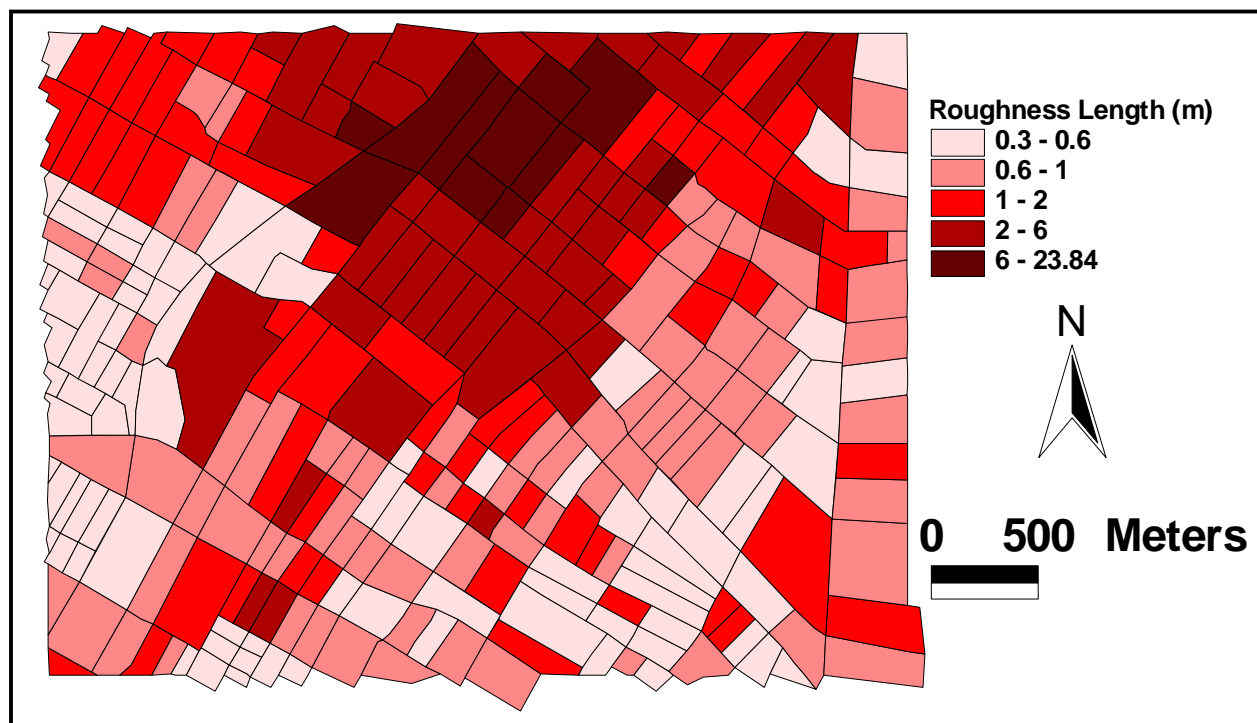
Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>3.20</b>	<b>0.64</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.40	0.48
Multifamily	5.50	1.10
Mixed	2.35	0.47
<b>Commercial &amp; Services</b>	<b>12.25</b>	<b>2.45</b>
Non-high-rise	6.60	1.32
High-rise	22.55	4.51
<b>Industrial</b>	<b>3.15</b>	<b>0.63</b>
<b>Transportation/Communications/Utilities</b>	<b>3.95</b>	<b>0.79</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>3.75</b>	<b>0.75</b>
<b>Mixed Urban or Built-up</b>	<b>6.00</b>	<b>1.20</b>
<b>Other Urban or Built-up</b>	<b>3.70</b>	<b>0.74</b>
Predominantly Vegetated	3.20	0.64
Predominantly Built-up	5.85	1.17
<b>Urban High-rise</b>	<b>15.8</b>	<b>3.16</b>
<b>Downtown Core Area</b>	<b>22.50</b>	<b>4.50</b>

**Table 15.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ): simple rules-of-thumb eqns. and plan-area-weighted average building height.

Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>5.20</b>	<b>1.04</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.50	0.50
Multifamily	8.30	1.66
Mixed	2.45	0.49
<b>Commercial &amp; Services</b>	<b>14.45</b>	<b>2.89</b>
Non-high-rise	8.95	1.79
High-rise	24.35	4.87
<b>Industrial</b>	<b>3.65</b>	<b>0.73</b>
<b>Transportation/Communications/Utilities</b>	<b>4.70</b>	<b>0.94</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>4.35</b>	<b>0.87</b>
<b>Mixed Urban or Built-up</b>	<b>9.05</b>	<b>1.81</b>
<b>Other Urban or Built-up</b>	<b>6.90</b>	<b>1.38</b>
Predominantly Vegetated	3.85	0.77
Predominantly Built-up	9.05	1.81
<b>Urban High-rise</b>	<b>21.30</b>	<b>4.26</b>
<b>Downtown Core Area</b>	<b>22.05</b>	<b>4.41</b>



**Figure 43.** Spatial distribution of displacement height ( $z_d$ ) in downtown Los Angeles computed using the simple rule-of-thumb (Eqn. (19)) and the plan-area-weighted average building height.



**Figure 44.** Spatial distribution of the roughness length ( $z_o$ ) in downtown Los Angeles computed using the simple rule-of-thumb (Eqn. 19) and the plan area-weighted average building height.

We also computed the  $z_d$  and  $z_o$  using two more complex equations suggested by Grimmond and Oke (1999). Although they compared results produced by different equations and concluded that it is difficult to measure their predictive accuracy, they did suggest an ordering of the morphometric equations. One set of equations ranked highly were those by Raupach (1994):

$$\frac{z_d}{z_H} = 1 - \left\{ \frac{1 - \exp[-(c_{d1} 2\lambda_f)^{0.5}]}{(c_{d1} 2\lambda_f)^{0.5}} \right\} \quad (21)$$

and

$$\frac{z_o}{z_H} = \left( 1 - \frac{z_d}{z_H} \right) \exp \left( -k \frac{U}{u_*} + \psi_k \right) \quad (22)$$

where

$$\frac{u_*}{U} = \min \left[ (c_S + c_R \lambda_f)^{0.5}, \left( \frac{u_*}{U} \right)_{\max} \right] \quad (23)$$

and  $\psi_k$  is the roughness sublayer influence function,  $U$  and  $u_*$  are the large-scale wind speed and the friction velocity, respectively,  $c_S$  and  $c_R$  are drag coefficients for the substrate surface at height  $z_H$  in the absence of roughness elements and of an isolated roughness element mounted on the surface, respectively, and  $c_{d1}$  is a free parameter. Raupach (1994) suggested  $\psi_k = 0.193$ ,  $(u_*/U)_{\max} = 0.3$ ,  $c_S = 0.003$ ,  $c_R = 0.3$ , and  $c_{d1} = 7.5$ . Using these values, a von Kármán constant ( $k$ ) of 0.4, and the values computed for the average building height and the average frontal area index, we calculated  $z_d \approx 5.93$  m and  $z_o \approx 1.27$  m. When using the plan-area-weighted average building height we found  $z_d \approx 8.44$  m and  $z_o \approx 1.81$  m. These values are very similar to those derived using the simple scheme described above (Eqns. (19) and (20)). Tables 16 and 17 list the computed  $z_d$  and  $z_o$  for each land use type using the average building height and the plan-area-weighted average building height, respectively.

**Table 16.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ):  
Raupach (1994) equations with the average building height

Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>3.24</b>	<b>0.71</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.16	0.42
Multifamily	6.13	1.40
Mixed	2.12	0.41
<b>Commercial &amp; Services</b>	<b>13.61</b>	<b>3.12</b>
Non-high-rise	6.09	1.23
High-rise	29.73	0.50
<b>Industrial</b>	<b>2.62</b>	<b>0.47</b>
<b>Transportation/Communications/Utilities</b>	<b>1.41</b>	<b>0.05</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>4.97</b>	<b>0.81</b>
<b>Mixed Urban or Built-up</b>	<b>6.47</b>	<b>1.47</b>
<b>Other Urban or Built-up</b>	<b>2.04</b>	<b>0.18</b>
Predominantly Vegetated	1.43	0.08
Predominantly Built-up	4.05	0.55
<b>Urban High-rise</b>	<b>20.38</b>	<b>3.59</b>
<b>Downtown Core Area</b>	<b>27.93</b>	<b>5.46</b>

**Table 17.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ):  
Raupach (1994) equations with the plan-area-weighted

Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>5.29</b>	<b>1.15</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.24	0.44
Multifamily	9.24	2.12
Mixed	2.20	0.43
<b>Commercial &amp; Services</b>	<b>16.06</b>	<b>3.68</b>
Non-high-rise	8.25	1.66
High-rise	32.11	5.31
<b>Industrial</b>	<b>3.04</b>	<b>0.54</b>
<b>Transportation/Communications/Utilities</b>	<b>1.68</b>	<b>0.06</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>5.77</b>	<b>0.94</b>
<b>Mixed Urban or Built-up</b>	<b>9.76</b>	<b>2.21</b>
<b>Other Urban or Built-up</b>	<b>3.80</b>	<b>0.33</b>
Predominantly Vegetated	1.71	0.10
Predominantly Built-up	6.27	0.85
<b>Urban High-rise</b>	<b>27.47</b>	<b>4.84</b>
<b>Downtown Core Area</b>	<b>27.38</b>	<b>5.35</b>

The second set of equations was derived by Macdonald et al. (1998). These equations incorporate the drag coefficient and displacement height into the expression for roughness length ( $z_o$ ):

$$\frac{z_d}{z_H} = 1 + \alpha^{-\lambda_p} (\lambda_p - 1) \quad (24)$$

and

$$\frac{z_o}{z_H} = \left( 1 - \frac{z_d}{z_H} \right) \exp \left\{ - \left( 0.5 \beta \frac{C_D}{k^2} \left( 1 - \frac{z_d}{z_H} \right) \lambda_f \right)^{-0.5} \right\} \quad (25)$$

where  $\alpha$  is an empirical coefficient,  $C_D$  is a drag coefficient,  $k$  is the von Kármán constant, and  $\beta$  is a correction factor for the drag coefficient (the net correction for several variables, including velocity profile shape, incident turbulence intensity, turbulence length scale, and incident wind angle, and for rounded corners). Macdonald et al. (1998) recommended for staggered arrays of cubes that  $\alpha \approx 4.43$  and  $\beta \approx 1.0$ . These values were used by Grimmond and Oke (1999) and are also used here. We also set  $C_D = 1.2$  (the same value used Grimmond and Oke (1999) in their analysis) and the von Kármán constant  $k = 0.4$ . Using these values and the mean building height we found  $z_d \approx 6.60$  m and  $z_o \approx 0.80$  m for the Los Angeles study area. Using the plan-area-weighted average building height we found  $z_d \approx 9.39$  m and  $z_o \approx 1.14$  m. This method gives smaller values of  $z_o$  compared to the values computed using the Raupach (1994) equations and slightly larger  $z_d$  values. Tables 18 and 19 list the computed  $z_d$  and  $z_o$  for each land use for the average building height and the plan-area-weighted average building height, respectively.

Table 20 compares the computed aerodynamic roughness parameters to those calculated for other cities. The roughness parameters shown in Table 20 for Los Angeles were calculated using the Raupach (1994) equations with the plan-area-weighted average building height. The values for Los Angeles are comparable to values from other locations. The Industrial parameters are very similar, while the Downtown parameters are greater than those calculated for other cities. Our values for the Residential land uses are nearly within the range of values computed for other cities. The computed roughness length of 0.44 m for the tract of High-density Single-family Residential using the Raupach (1994) equations is within the range of 0.4-0.7 m presented by Wieringa (1993) for homogeneous suburban low buildings.

**Table 18.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ):  
Macdonald et al. (1998) equations with the average building height

Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>3.53</b>	<b>0.46</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.46	0.27
Multifamily	6.22	0.99
Mixed	2.53	0.24
<b>Commercial &amp; Services</b>	<b>12.87</b>	<b>2.56</b>
Non-high-rise	6.57	0.88
High-rise	26.05	6.21
<b>Industrial</b>	<b>4.08</b>	<b>0.13</b>
<b>Transportation/Communications/Utilities</b>	<b>0.57</b>	<b>0.05</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>5.53</b>	<b>0.12</b>
<b>Mixed Urban or Built-up</b>	<b>7.23</b>	<b>0.84</b>
<b>Other Urban or Built-up</b>	<b>1.04</b>	<b>0.27</b>
Predominantly Vegetated	0.76	0.10
Predominantly Built-up	3.31	0.65
<b>Urban High-rise</b>	<b>18.25</b>	<b>4.10</b>
<b>Downtown Core Area</b>	<b>24.25</b>	<b>6.07</b>

**Table 19.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ):  
Macdonald et al. (1998) equations with the plan-area-weighted average building height

Land Use Class	$z_d$ (m)	$z_o$ (m)
<b>Residential</b>	<b>5.74</b>	<b>0.74</b>
Low-density Single-family (< 8 units/hectare)	---	---
High-density Single-family ( $\geq 8$ units/hectare)	2.56	0.28
Multifamily	9.38	1.50
Mixed	2.64	0.25
<b>Commercial &amp; Services</b>	<b>15.18</b>	<b>3.02</b>
Non-high-rise	8.91	1.19
High-rise	28.13	6.71
<b>Industrial</b>	<b>4.73</b>	<b>0.15</b>
<b>Transportation/Communications/Utilities</b>	<b>0.68</b>	<b>0.06</b>
<b>Mixed Industrial &amp; Commercial</b>	<b>6.41</b>	<b>0.14</b>
<b>Mixed Urban or Built-up</b>	<b>10.90</b>	<b>1.26</b>
<b>Other Urban or Built-up</b>	<b>1.94</b>	<b>0.50</b>
Predominantly Vegetated	0.91	0.12
Predominantly Built-up	5.12	1.00
<b>Urban High-rise</b>	<b>24.61</b>	<b>5.53</b>
<b>Downtown Core Area</b>	<b>23.77</b>	<b>5.95</b>

**Table 20.** Displacement height ( $z_d$ ) and roughness length ( $z_o$ ) for different cities

Location	Land Use Class	$z_d$ (m)	$z_o$ (m)	Source
<b>Los Angeles, CA</b>	<b>Multifamily residential</b>	<b>9.24</b>	<b>2.12</b>	<b>This report*</b>
Arcadia, CA	Suburban residential	6.75	1.50	Grimmond and Oke (1999), Fig. 4
Vancouver, BC, Canada	Suburban residential	4.10	0.95	Grimmond and Oke (1999), Fig. 4
Chicago, IL	Suburban residential	4.00	0.75	Grimmond and Oke (1999), Fig. 4
Miami, FL	Suburban residential	3.25	0.80	Grimmond and Oke (1999), Fig. 4
Sacramento, CA	Suburban residential	3.10	0.75	Grimmond and Oke (1999), Fig. 4
San Gabriel, CA	Suburban residential	2.35	0.6	Grimmond and Oke (1999), Fig. 4
<b>Los Angeles, CA</b>	<b>High-density single-family residential</b>	<b>2.24</b>	<b>0.44</b>	<b>This report*</b>
Tucson, AZ	Suburban residential	2.10	0.40	Grimmond and Oke (1999), Fig. 4
Vancouver, BC, Canada	Light industrial	2.25	0.5	Grimmond and Oke (1999), Fig. 4
<b>Los Angeles, CA</b>	<b>Industrial</b>	<b>3.04</b>	<b>0.54</b>	<b>This report*</b>
<b>Los Angeles, CA</b>	<b>Commercial &amp; services high-rise</b>	<b>32.11</b>	<b>5.31</b>	<b>This report*</b>
<b>Los Angeles, CA</b>	<b>Downtown core area</b>	<b>27.38</b>	<b>5.35</b>	<b>This report*</b>
Vancouver, BC, Canada	Central city	20.00	4.50	Grimmond and Oke (1999), Fig. 4
Mexico City, Mexico	Central city	8.00	1.60	Grimmond and Oke (1999), Fig. 4

\* LA values computed using the Raupach (1994) equations and the plan-area-weighted building height

#### 4.0 Summary

This report summarizes the results of the derivation of building morphological (i.e., urban terrain) characteristics for a 12.0 km<sup>2</sup> area of downtown Los Angeles, California. A three-dimensional building dataset and detailed land use/land cover information were integrated and analyzed using a geographic information system (GIS). Building height characteristics (e.g., mean height, height variance, height histograms) were determined for the entire study area and broken down by land use type. Parameters describing the urban morphology were also calculated including the building plan area fraction ( $\lambda_p$ ), building area density ( $a_p(z)$ ), rooftop area density ( $a_r(z)$ ), frontal area index ( $\lambda_f$ ), frontal area density ( $a_f(z)$ ), complete aspect ratio ( $\lambda_c$ ), building surface area to plan area ratio ( $\lambda_b$ ), and the height-to-width ratio ( $\lambda_s$ ). These urban morphological parameters were calculated for the entire study area, for different land use types, and in some cases as a function of height above ground elevation. Using the urban morphological parameters, the aerodynamic roughness length ( $z_o$ ) and displacement height ( $z_d$ ) were calculated for the entire study area and for each land use type using standard morphometric equations. Most of the calculated morphometric parameters were found to be similar to values computed for other cities by other researchers. Synthesis of the results indicates that the urban morphological parameters vary significantly for different land uses. Moreover, the urban land uses containing tall buildings were found to have significantly different morphological characteristics than other urban land uses.

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## **APPENDIX 1**

### **SCAG Land Use Types**

**Table A1.1. SCAG LULC classification system.**

Level I	Level II	Level III	Level IV
<b>Urban or Built-Up (1000)</b>	Residential (1100)	Single Family Residential (1110)	High Density Single Family Residential (1111)
		Multi-Family Residential (1120)	Low Density Single Family Residential (1112)
			Mixed Multi-Family Residential (1121)
			Duplexes, Triplexes, and 2/3 unit Condos (1122)
			Low-Rise Apartments, Condos, Townhouses (1123)
			Medium-Rise Apartments and Condos (1124)
			High-Rise Apartments and Condos (1125)
		Mobile Homes and Trailer Parks (1130)	Trailer Parks - High Density (1131)
			Trailer Parks - Low Density (1132)
		Mixed Residential (1140)	
		Rural Residential (1150)	Rural Residential High Density (1151)
			Rural Residential Low Density (1152)
	Commercial and Services (1200)	General Office Use (1210)	Low- to Medium-Rise Major Office (1211)
			High-Rise Major Office (1212)
			Skyscrapers (1213)
		Retail Stores and Commercial Services (1220)	Regional Shopping Center (1221)
			Retail Centers (1222)
			Modern Strip Development (1223)
			Older Strip Development (1224)
		Other Commercial (1230)	Commercial Storage (1231)
			Commercial Recreation (1232)
			Hotels and Motels (1233)
			Attended Pay Public Parking (1234)
		Public Facilities (1240)	Government Offices (1241)
			Police and Sheriff Stations (1242)
			Fire Stations (1243)
			Major Medical Health Care (1244)
			Religious Facilities (1245)
			Other Public Facilities (1246)
			Non-Attended Public Parking (1247)
		Special Use Facilities (1250)	Correctional Facilities (1251)
			Special Care Facilities (1252)
			Other Special Facilities (1253)
		Educational Institutions (1260)	Pre-Schools/Day Care Centers (1261)
			Elementary Schools (1262)
			Junior High Schools (1263)
			Senior High Schools (1264)
			Colleges and Universities (1265)
			Trade Schools (1266)
		Military Installations (1270)	Military Base (Built-Up Areas) (1271)
			Vacant Military Area (1272)
			Military Air Field (1273)
	Industrial (1300)	Light Industrial (1310)	Manufacturing, Assembly, and Industrial (1311)
			Motion Picture and Television Studios (1312)
			Packing Houses and Grain Elevators (1313)

		Research and Development (1314)
	Heavy Industrial (1320)	Manufacturing (1321) Petroleum Refining and Processing (1322) Open Storage (1323) Major Metal Processing (1324) Chemical Processing (1325)
	Extraction (1330)	Mineral Extraction - Other than Oil and Gas (1331) Mineral Extraction - Oil and Gas (1332)
	Wholesaling and Warehousing (1340)	
Transportation, Communication, and Utilities (1400)	Transportation (1410)	Airports (1411) Railroads (1412) Freeways and Major Roads (1413) Park and Ride Lots (1414) Bus Terminals and Yards (1415) Truck Terminals (1416) Harbor Facilities (1417) Navigation Aids (1418)
	Communication Facilities (1420)	
	Utility Facilities (1430)	Electrical Power Facilities (1431) Solid Waste Disposal Facilities (1432) Liquid Waste Disposal Facilities (1433) Water Storage Facilities (1434) Natural Gas and Petroleum Facilities (1435) Water Transfer Facilities (1436) Improved Flood Waterways and Structures (1437) Mixed Wind Energy Generation (1438)
	Maintenance Yards (1440)	
	Mixed Transportation (1450)	
	Mixed Transportation and Utility (1460)	
Mixed Commercial and Industrial (1500)		
Mixed Urban (1600)		
Under Construction (1700)		
Open Space and Recreation (1800)	Golf Courses (1810)	
	Local Parks and Recreation (1820)	Parks (1821)
	Regional Parks and Recreation (1830)	
	Cemeteries (1840)	
	Wildlife Preserves and Sanctuaries (1850)	
	Specimen Gardens and Arboreta (1860)	
	Beach Parks (1870)	
	Other Open Space and Recreation (1880)	
Urban Vacant (1900)		
<b>Agriculture (2000)</b>	Cropland and Improved Pasture Land (2100)	Irrigated Cropland and Improved Pasture (2110) Non-Irrigated Cropland and

		Improved Pasture (2120)	
	Orchards and Vineyards (2200)		
	Nurseries (2300)		
	Dairy and Intensive Livestock (2400)		
	Poultry Operations (2500)		
	Other Agriculture (2600)		
	Horse Ranches (2700)		
<b>Vacant (3000)</b>	Vacant Undifferentiated (3100)		
	Abandoned Orchards and Vineyards (3200)		
	Vacant with Limited Improvements (3300)		
	Beaches (Vacant) (3400)		
<b>Water (4000)</b>	Water, Undifferentiated (4100)		
	Harbor Water Facilities (4200)		
	Marina Water Facilities (4300)		
	Water Within a Military Installation (4400)		
	Area of Inundation (4500)		
<b>No Data (0)</b>			

## **Appendix 2**

### **Description of Land Use Types**

The land use/land cover classification we used for the building analysis was divided into two schemes as shown in Table A2.1. The first scheme corresponds to the Anderson Level 2 classification used by the USGS for its standard national dataset. The second scheme includes the subdivision of the Anderson Level 2 **Residential**, **Commercial & Services**, and **Other Urban or Built-up** categories. Descriptions of the 7-category and 12-category schemes follow Table A2.1. In addition to the multi-level classification we also categorize all the land use parcels that contain high-rise buildings as **Urban High-rise**. Finally, using aerial photographs and other information we defined the downtown city center area and termed this land use as **Downtown Core Area**. Note that **Urban High-rise** and **Downtown Core Area** contain a mix of land use types from Table A2.1.

**Table A2.1.** The 7-category and 12-category land use classification schemes

Land Use Class
<b>Residential</b>
Low-density Single-family ( $\leq 8$ units/hectare)
High-density Single-family ( $> 8$ units/hectare)
Multifamily
Mixed
<b>Commercial &amp; Services</b>
Non-high-rise
High-rise
<b>Industrial</b>
<b>Transportation/Communications/Utilities</b>
<b>Mixed Industrial &amp; Commercial</b>
<b>Mixed Urban or Built-up</b>
<b>Other Urban or Built-up</b>
Predominantly Vegetated
Predominantly Built-Up
<b>Urban High-rise</b>
<b>Downtown Core Area</b>

\* The 7-category scheme is shown in boldface, the 12-category scheme contains additional categories that are indented

### **Residential**

Includes areas of single-family residences, multi-unit dwellings, mobile homes, and mixtures of residential land use types.

*Low-density Single-family:* Detached residential housing units with an average density less than or equal to 8 units per hectare ( $\sim 3$  units/acre).

*High-density Single-family:* Detached residential housing units with an average density greater than 8 units per hectare ( $\sim 3$  units/acre).

*Multifamily:* Residential housing units designed to contain multiple families in a single structure. Includes apartments and condominiums.

*Mixed:* A mixture of low-density single-family, high-density single-family, and multifamily residential land uses.

**Commercial & Services**

Commercial & Services land use includes areas which are used predominantly for business or the sale of products and their associated services. This category is divided into non-high-rise and high-rise land use types in the 12-category scheme. Includes shopping malls, business districts, office buildings, strip malls, educational and institutional, and other commercial areas.

**Industrial**

Industrial land use includes areas where manufacturing, assembly, processing, packaging, or storage of products takes place.

**Transportation/Communication/Utilities**

Areas devoted to major transportation, such as airports, freeways, roads, railways and harbor facilities. Also included are areas devoted to communications and utilities.

**Mixed Industrial & Commercial**

Areas included are a mixture of industrial and commercial land uses.

**Mixed Urban or Built-Up**

Areas included are a mixture of the other urban land uses with none being the dominant.

**Other Urban or Built-Up**

Other land use areas that cannot be categorized in the above categories. Urban vegetation and bare soil classes are categorized in this class for this scheme.

*Predominantly Vegetated:* Areas included are urban land uses that are predominantly vegetation, such as golf courses, parks, recreation fields, cemeteries, and so on. Some buildings may be contained on the site.

*Predominantly Built-up:* Includes urban land uses not categorized in any of the above land uses and that are not predominantly vegetated. These land uses are generally ambiguous or unknown.

**Urban High-rise**

Land use that contains high-rise buildings. High-rise buildings are subjectively selected based on their relative size compared to the surrounding buildings. In general, Urban High-rise was designated for land uses containing buildings with heights in excess of 10 stories.

**Downtown Core Area**

Subjective designation of the downtown core area based on aerial photograph, street maps, building datasets, and other information.

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## **Appendix 3**

### **SCAG Land Use Aggregation**

The aggregation of the SCAG land use to more general levels is usually straightforward because the base dataset is in a modified Anderson Level III/IV classification. The Anderson classification scheme is divided into sub-categories of land use with increasing detail, but the sub-categories are easily aggregated up to the general Anderson Level 2 categories (those used in the USGS LULC dataset). Table A3.1, shown below, lists the mapping from SCAG land use to the 7-category and 12-category schemes. We also note which land uses are mapped to Urban High-rise. Note that in some cases land use can be classified as Urban High-rise based on other information than the mapping shown in Table A3.1.

**Table A3.1. SCAG LULC aggregation.**

SCAG Land Use Type	Classification Level 1	Classification Level 2	High-rise or Non-high-rise
High Density Single Family Residential (1111)	Residential	High-density Single-family Residential	Non-high-rise
Mixed Multi-Family Residential (1121)	Residential	Multifamily Residential	Non-high-rise
Low-Rise Apartments, Condos, Townhouses (1123)	Residential	Multifamily Residential	Non-high-rise
Medium-Rise Apartments and Condos (1124)	Residential	Multifamily Residential	High-rise
High-Rise Apartments and Condos (1125)	Residential	Multifamily Residential	High-rise
Mixed Residential (1140)	Residential	Mixed Residential	Non-high-rise
Low- to Medium-Rise Major Office (1211)	Commercial & Services	High-rise Commercial & Services	High-rise
High-Rise Major Office (1212)	Commercial & Services	High-rise Commercial & Services	High-rise
Skyscrapers (1213)	Commercial & Services	High-rise Commercial & Services	High-rise
Regional Shopping Center (1221)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Retail Centers (1222)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Modern Strip Development (1223)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Older Strip Development (1224)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Hotels and Motels (1233)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Attended Pay Public Parking (1234)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Government Offices (1241)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Police and Sheriff Stations (1242)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Fire Stations (1243)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Major Medical Health Care (1244)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Religious Facilities (1245)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Other Public Facilities (1246)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Non-Attended Public Parking (1247)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Correctional Facilities (1251)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Other Special Facilities (1253)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Elementary Schools (1262)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise

Junior High Schools (1263)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Senior High Schools (1264)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Colleges and Universities (1265)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Trade Schools (1266)	Commercial & Services	Non-high-rise Commercial & Services	Non-high-rise
Manufacturing, Assembly, and Industrial (1311)	Industrial	Industrial	Non-high-rise
Open Storage (1323)	Industrial	Industrial	Non-high-rise
Wholesaling and Warehousing (1340)	Industrial	Industrial	Non-high-rise
Railroads (1412)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Freeways and Major Roads (1413)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Park and Ride Lots (1414)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Bus Terminals and Yards (1415)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Truck Terminals (1416)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Communication Facilities (1420)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Maintenance Yards (1440)	Transportation/Communications/Utilities	Transportation/Communications/Utilities	Non-high-rise
Mixed Commercial and Industrial (1500)	Mixed Industrial & Commercial	Mixed Industrial & Commercial	Non-high-rise
Mixed Urban (1600)	Mixed Urban or Built-up	Mixed Urban or Built-up	Non-high-rise
Under Construction (1700)	Other Urban or Built-up	Other Predominantly Built-up	Non-high-rise
Local Parks and Recreation (1820)	Other Urban or Built-up	Predominantly Vegetated	Non-high-rise
Parks (1821)	Other Urban or Built-up	Predominantly Vegetated	Non-high-rise
Other Open Space and Recreation (1880)	Other Urban or Built-up	Predominantly Vegetated	Non-high-rise
Urban Vacant (1900)	Other Urban or Built-up	Predominantly Vegetated	Non-high-rise
No Data (0)	No Data	No Data	No Data